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email: journal@ougs.org

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Cover illustration: Thin sections of several different habits of barite. Photographs: Jane Clarke.

Botryoidal barite Mag 538; ppl.	Acicular barite Mag 549; xpl.	Poikilotopic barite Mag 530; xpl.
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A geological framework for the evolution of the Trent Valley and its landscapes

J N Carney, British Geological Survey, Keyworth, Nottingham

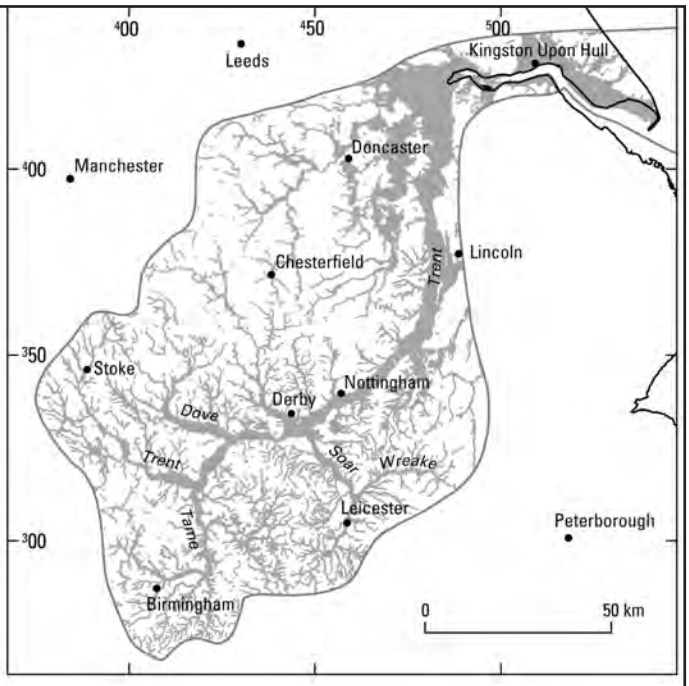

Figure 1. Distribution of Trent floodplains defined by their deposits (alluvium and 'floodplain terrace'). Extracted from BGS digital databases (DiGMapGB)

Introduction

The landscapes and drainage systems of southern Britain are widely considered to have developed during the Cenozoic Period (see review in Gibbard & Lewin 2003) following the destruction of the shelf sea in which Jurassic and, ultimately, Cretaceous strata were deposited. It can also be argued, however, that landscapes are the culmination of a geological inheritance stretching back over hundreds of millions of years. The trunk streams of the Trent catchment system (Figure 1) demonstrate this, in that they are spatially related to outcrops of Triassic strata, shown in Figure 2. What are not so obvious are the tectonic factors that have exerted an underlying control over drainage and landscape development. This article briefly assesses the geological framework of the region, but also emphasises the role of geological structure in moulding the physiography of the Trent valley through time.

The rocks that frame the Trent basin (Figure 2) and its varied landscapes are the products of a complex geological history spanning at least 600 million years. They record periods of volcanic activity, igneous intrusion and sedimentation separated by episodes of deformation, metamorphism, uplift and erosion. The structural events are of particular importance because they have determined patterns of major faults that have been periodically reactivated, controlling the geomorphological development of the region and, ultimately, the location of the modern Trent trunk streams. Such structures are the response of the Midlands' crust to fundamental changes in prevailing plate tectonic regimes, as England 'drifted' progressively northwards across the Equator and into the present temperate latitudes where, in the Quaternary, combinations of fluvial erosion, periglaciation and ice action have completed the Trent landscape evolution.

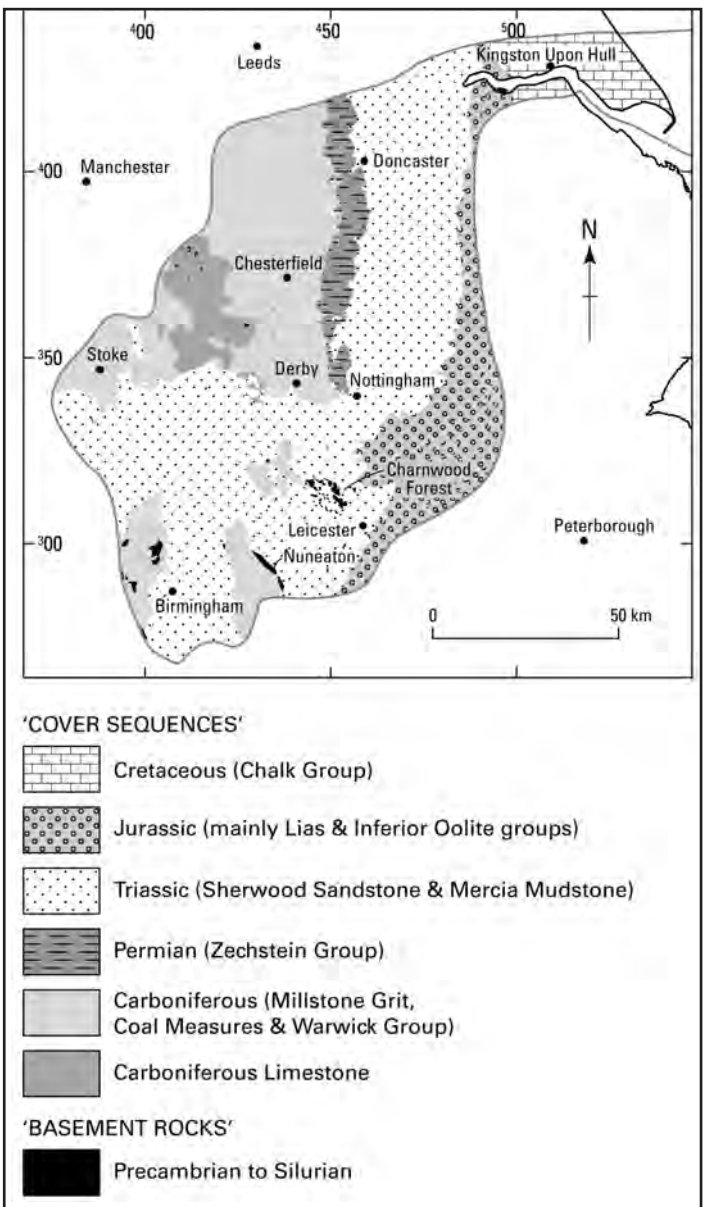

Figure 2. Simplified geology of the Trent catchment basin.

Precambrian to early Devonian – establishing the basement

The basement (i.e. pre-Carboniferous) rocks are the fundamental crustal 'building blocks' of England. In the Trent region they crop out as small, structurally controlled inliers at Charnwood Forest, Nuneaton and around Birmingham (Figure 2). The former two areas reveal Precambrian rocks, mainly volcaniclastic sedimentary strata together with massive andesites and dacites of probable subvolcanic origin, and intrusive rocks. Chemical analyses of the more primary igneous components show that the parental magmas were similar to those of modern evolved volcanic arcs generated above a subduction zone (Pharaoh *et al.* 1987a). They further indicate that both Precambrian outcrops belong to a single basement entity, known as the Charnwood Terrane, which formed one segment of the complex Avalonian volcanic arc system that was active off the margin of Gondwana between about 700 and

Figure 3. Precambrian volcanic breccia at the 'Bomb Rocks', Charnwood Lodge Nature Reserve, Charnwood Forest.

560 Ma (Pharaoh & Carney 2000). Structural considerations suggest that this crustal block was juxtaposed with a different Precambrian volcanic arc terrane along the northerly trending 'Malvern lineament' (Lee *et al.* 1990), the tectonic influence of which will be discussed later.

In Charnwood Forest, the Precambrian rocks form a distinctive landscape of rolling hills crowned by craggy knolls, with intervening valleys excavated in the much softer, unconformable Triassic strata. They are divided (Moseley & Ford 1985) into two lower groups of volcaniclastic rocks, of which the younger Maplewell Group contains primary volcanic components in the form of tuffs and extremely coarse, bouldery fragmental rocks (Figure 3). The latter are interpreted as the products of pyroclastic block flows, similar to the recent eruptions on Montserrat in the Caribbean island arc (Carney 1999). Such rocks indicate close proximity to the Precambrian volcanic centres, one of which, at Bardon Hill, was visited during this Symposium. The Caldecote Volcanic Formation of Nuneaton differs, in that it is characterised by thick beds of crystal-lapilli tuff with abundant whole or fragmentary quartz and plagioclase crystals (Bridge *et al.* 1998). As in Charnwood Forest, however, these rocks are cut by two sets of quartz diorite intrusions, the youngest of which, at Nuneaton, yielding a Late Neoproterozoic U/Pb age of 603 ± 2 Ma (Tucker & Pharaoh 1991). The Charnwood Forest succession is famous for its fossil fauna (Boynton & Ford 1995), which includes *Charnia,* a major index fossil of the newly established Ediacaran Stage – the final unit of Precambrian time - which is considered to have terminated at 543 Ma.

By the close of Precambrian time, the various volcanic arc terranes had been tectonically amalgamated to form the elongate microcontinent of Eastern Avalonia (Gibbons & Horák 1996; Pharaoh & Carney 2000). The sea then invaded this eroded landmass, depositing a transgressive sedimentary sequence, the fullest development of which is exposed within the Nuneaton inlier (Figure 2). It commences with the Hartshill Sandstone Formation, deposited in nearshore, tidally influenced environments (Brasier *et al.* 1978; Bridge *et al.* 1998), which rests with erosional unconformity on deeply weathered Precambrian rocks (Carney 1995). Near the top, this formation contains a minor depositional hiatus represented by the Home Farm Member ('Hyolithes Limestone'), a condensed sequence of Lower Cambrian (Tommotian-Atdabanian) age hosting the earliest shelly fossils to be found in Britain (Brasier 1984). Trilobite-bearing mudrocks of the overlying Stockingford Shale Group are at least 700 m thick at Nuneaton where the topmost unit, the Merevale Shale Formation, has fossils indicative of a lowermost Ordovician (Tremadoc) age (Taylor & Rushton 1971). Remarkably, Tremadocian mudrocks are also encountered in deep boreholes beneath Leicester (Molyneux 1991), 33 km to the east. As borehole cores indicate that these rocks commonly dip steeply, the most likely explanation for their regional extent, without invoking extraordinary thicknesses, is that the Stockingford Shale Group has been tectonically repeated across faults and folds in a structurally complex basement.

In Charnwood Forest, the suggestion of a Lower Cambrian age for the youngest, Brand Group rocks is a recent major development that has followed from the discovery of *Teichichnus,* a Phanerozoic trace fossil, on local headstones carved from quarries in the Swithland Formation (Bland & Goldring 1995). The Brand Group may thus be a close contemporary of the Stockingford Shale Group, although there is no other faunal evidence to corroborate this.

Further rock sequences of probable early Ordovician (Tremadoc) age to the west and north of the Birmingham conurbation (Figure 2) are represented by the Barnt Green Volcanic Formation, which includes water-laid tuffs, and the overlying Lickey Quartzite Formation, the latter probably deposited in nearshore, tidally influenced environments (Molyneux in Old *et al.* 1991; Powell *et al.* 2000). There are possible links between these isolated exposures and the more complete successions of the Welsh Basin, which includes igneous rocks generated by the subduction of Iapetus oceanic crust beneath Avalonia.

To the east, around Nuneaton, Croft and Mountsorrel, younger (Caradoc to Ashgill) Ordovician rocks consist entirely of igneous intrusions emplaced within the Precambrian and early Ordovician sequences. Their calc-alkaline chemistry is compatible with magma generation during continued subduction of the Iapetus plate beneath the Midlands, when the Avalonia microcontinent was moving northwards (Pharaoh 1999). In the Trent region, these igneous intrusions are major sources of hard-rock aggregate and are well known from their exposures in several large quarries. They fall into two chemically and mineralogically distinct 'clans': the Midlands Minor Intrusive Suite, of olivine-bearing lamprophyres and hornblende diorites exemplified by exposures around Nuneaton (Bridge *et al.* 1998) and, farther east, the granodiorites and quartz-diorites of the Mountsorrel Complex and South Leicestershire Diorites respectively. The latter rocks are chemically comparable with the Caradocian intrusions of Snowdonia and the Lake District, confirming the extension of the Caledonian magmatic system - the 'concealed Caledonides' of Pharaoh *et al.* (1987b) – down the eastern side of England.

Silurian rocks are preserved only in the far west of the region, their most extensive outcrop being the inlier centred on Walsall, north of Birmingham (Figure 2). They locally rest unconformably on the Lickey Quartzite Formation and their deposition is attributed to a marine transgression that occurred in Llandovery (Telychian) times (Powell *et al.* 2000). Silurian strata mainly consist of mudstones interbedded with limestone-dominant units, the most famous of which is the Much Wenlock Formation, exposed at the Wren's Nest Nature Reserve. The overlying mudstones of the Lower Ludlow

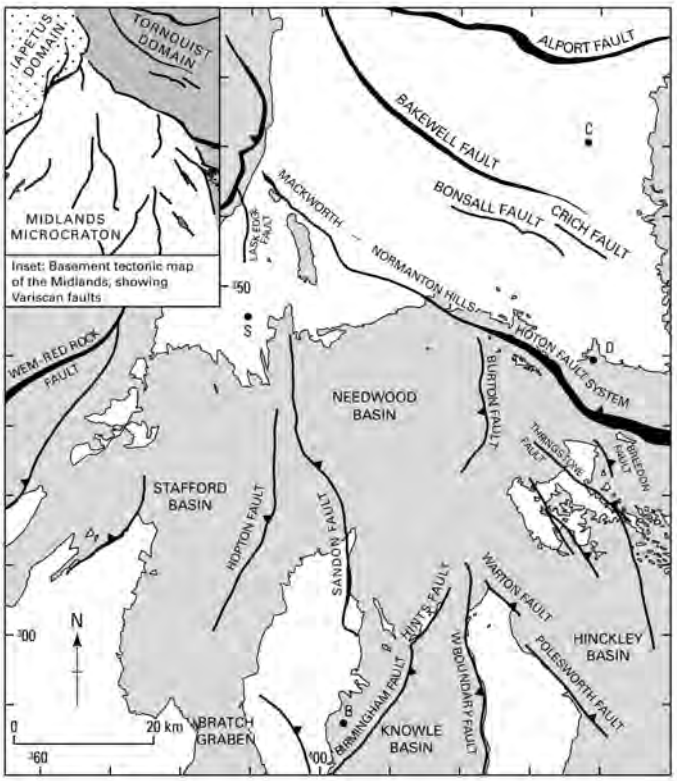

Figure 4. Triassic outcrop (shaded) and named extensional basins, overlaid with major Variscan faults. Inset shows the Precambrian to Palaeozoic tectonic domains that influence the underlying structure of the Trent region. Data from Smith *et al.* (2005). Urban conurbations shown are: B, Birmingham; C, Chesterfield; D, Derby; S, Stoke.

Shales and Ledbury Formation are the youngest preserved elements of this transgressive sequence, the deposition of which would have been terminated, in very latest Silurian or earliest Devonian times, by the onset of the end-Caledonian (Acadian) Orogeny.

Forming the structural template - the Acadian Orogeny

This orogeny is attributed to the docking of Avalonia with the Laurentian plate along the Iapetus and Tornquist suture zones during late Silurian times (Soper & Woodcock 2003). It influenced the whole of southern Britain but, because of the younger rock cover, its effects in the Trent region can mainly be deciphered by the structural legacy that it left behind. The basement structural orientations vary significantly across the Trent catchment between the three tectonic domains shown in the inset of Figure 4 (Smith *et al.* 2005). The least deformed domain is represented by the Midlands Microcraton, where northerly fault systems are most probably inherited from the latest Precambrian phase of volcanic arc amalgamation along the 'Malvern lineament', discussed above. Those fault systems are truncated to the west by north-easterly structures of the Iapetus domain, representing deformation within the Welsh Basin. In the east, they are beheaded by the structures of the Tornquist domain, reflecting discontinuities within the concealed Caledonides basement of eastern England.

Charnwood Forest provides an important window on local Tornquist deformation, which here was particularly intense and accompanied by upper greenschist metamorphism (Merriman & Kemp 1997). The structures that resulted included north-west trending displacements such as the Thringstone Fault and the adjacent Charnwood anticline, as well as a west-north-westerly trending, penetrative cleavage fabric (Carney *et al.* 2001). Argon isotope dating of those mica cleavage fabrics suggest that in this part of Britain the Acadian event occurred in very latest Silurian times (unpublished BGS data). The tectonic control exerted by these Acadian structures, however, persisted 'posthumously' long after the orogeny had ceased and the Charnwood cleavage direction had a particular influence. It is seen in the orientation of Variscan structures such as the Mackworth-Hoton Fault System and other parallel Tornquist domain faults (Figure 4), some of which remained periodically active into post-Jurassic times.

Late Devonian to end-Carboniferous sedimentary and structural events

The sheer variety of sedimentary rocks produced during this period is a major feature of Trent basin geology, and an important landscape agency. It also, however, reflects the underlying influence of the Variscan tectonic cycle, which was developing throughout the Carboniferous Period in response to stresses transmitted during compression along the Variscan suture and associated fold belt, which lay across southern Britain.

Following the fifty million years or so of erosion after the Acadian uplifts, a change to at least localised subsidence is detected in latest Devonian times, with the accumulation of mainly continental, fluvial deposits. These are only preserved along the western margin of the Nuneaton inlier, as the Oldbury Farm Sandstone Formation (Bridge *et al.* 1998). Soon after, progressive crustal extension occurred behind the developing Variscan orogenic front, forming systems of deep, sediment-filled, asymmetric grabens across the northern part of the Trent region. This ushered in the syn-rift phase of Carboniferous deposition (Fraser & Gawthorpe 1990; 2003), which was controlled by faults with orientations that indicate a strong underlying control by the west-north-westerly Acadian cleavage direction revealed in Charnwood Forest. In the Trent area the deepest of these troughs was the Widmerpool half-graben (or 'Gulf'), with about 5.5 km of turbiditic, mud-dominated sediment accumulated during the Early Carboniferous (Dinantian) Period (Carney *et al.* 2001) along the northern, hangingwall side of the Mackworth-Hoton Fault System (Figure 4). Coral reefs and carbonate shelves were established in the shallower marine environments created in parts of this tilted block and graben topography (Miller & Grayson 1982). They belong to the fossiliferous Carboniferous Limestone Supergroup, a major landscape-forming sequence exposed (Figure 2) within the core of the Pennine Anticline and visited at the National Stone Centre, near Wirksworth, during this Symposium.

By Namurian times, crustal extension had largely ceased and sediments of the 'post-rift' phase (Fraser & Gawthorpe 1990) began to fill the remaining basins, eventually expanding outwards across the bounding faults. Turbiditic mudstones, siltstones and sandstones of the Edale Shales (now the Bowland Shale Formation) were the initial products of this cycle, which was followed by the southwards encroachment of the deltas that deposited the thick, feldspathic sandstones of the Millstone Grit Group. Their resistance to erosion, compared with the intervening mudstone beds, produces the spectacular 'edges' that dominate the landscape of the Dark Peak (Figure 5), seen on the Symposium visit to the area around Chatsworth House. Subsequently, during the Westphalian

Figure 5. Burbage Edge, Derbyshire; typical upland Carboniferous scenery developed on tilted sandstone beds of the Millstone Grit Group. The slope below the sandstone exposure is veneered by a periglacial waste-mantle of Late Devensian age.

Carboniferous Epoch, a vast, featureless, equatorial delta plain occupied the gradually subsiding Pennine Basin. The strata deposited belong to the Pennine Coal Measures Group and have proved vital to the industrial development of the region. They mostly comprise repeated sedimentary cycles (Guion *et al.* 1995), commencing with dark grey to black, lacustrine or marine mudstones passing upwards into sandy siltstones of overbank or lacustrine delta facies, then into channel sandstones that are commonly surmounted by a seatearth (palaeosol horizon) and coal seam (swamps and mires).

This lithological diversity, combined with later erosion, has produced a strongly-featured terrain that is typical of all Coal Measure outcrops.

This essentially quiet geological interval was terminated by tectonic movements that ushered in better-drained, alluvial environments in which were deposited the predominantly red-coloured mudstones and sandstones of the Warwickshire Group (formerly 'Barren Measures'). These sequences are exemplified by the exposures in the South Staffordshire and Warwickshire coalfields, west of Birmingham and Nuneaton respectively (Figure 2). The reddened, ferruginous palaeosol horizons distinctive to many parts of this group signify localised block uplifts that were a prelude to widespread inversion of the Pennine Basin during the culmination of the Variscan Orogeny in latest Carboniferous to earliest Permian times (Besly 1988).

The final Variscan movements were part of the consolidation of the Pangaea supercontinent. Their most obvious manifestation was the folding that formed the limestone-cored Pennine Anticline in the north (Figure 2). Different structural styles prevailed farther south, where the Pennine Basin was inverted as a series of fault-bounded synclinal structures. Figure 4 shows that many of the controlling faults have northerly trends, and this reflects the underlying but persistent influence of structures associated with the 'Malvern lineament' Precambrian terrane boundary, discussed above. The end-Carboniferous movements had economic repercussions for the region; they were responsible for the expulsion of hot, metal-rich basinal fluids that gave rise to the Derbyshire lead and fluorspar mineralisation (e.g. Ford 2001),

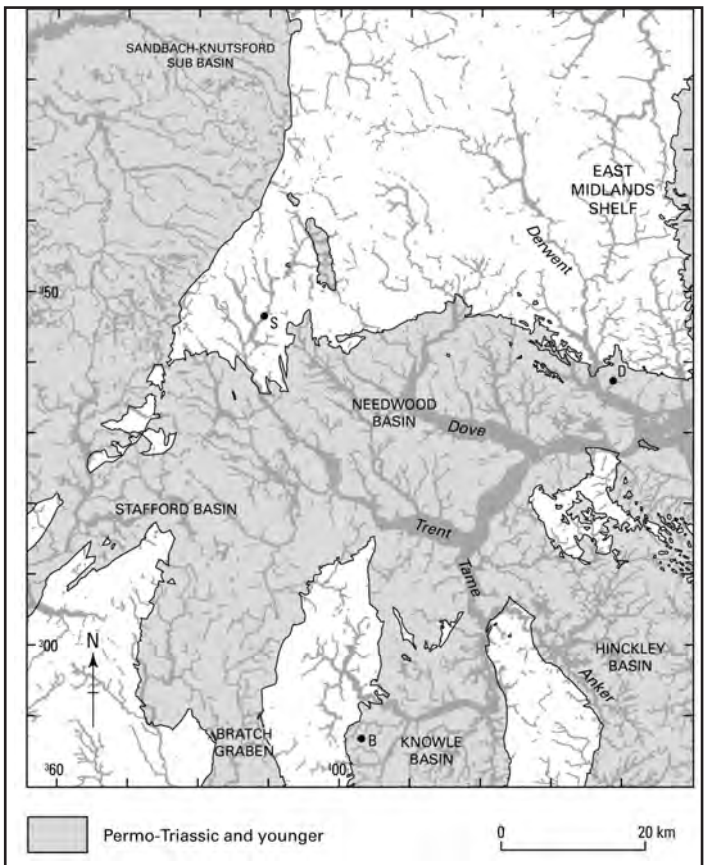

Figure 6. Outcrop of mainly Permo-Triassic strata (shaded), with named Triassic basins (see Figure 4), in relation to the distribution of Trent floodplain deposits.

and they formed structures that favoured oil migration and accumulation in the East Midlands (Fraser & Gawthorpe 2003).

Permian to end-Triassic sedimentation and structural development

Throughout most of the Permian, a period of some 40 million years duration, the land surface of eastern England was undergoing erosion within an arid, rock-desert just to the north of the Equator, in the heart of the Pangaea supercontinent. Late in Permian times, however, marginal marine sedimentation occurred as the Southern North Sea Basin encroached across the northern parts of the Trent region. Strata of the Zechstein Group were deposited (Figure 2), their main representative being the Cadeby Formation (Lower Magnesian Limestone), which forms the impressive escarpment overlooking the Nottinghamshire-Derbyshire coalfield at places such as Bolsover.

By earliest Triassic times, crustal extension associated with the lead-up to Atlantic opening triggered widespread subsidence across the northern margin of Pangaea (Chadwick *et al.* 1989). In the west of the Trent region this subsidence was greatly accentuated by the development of deep, fault-bounded extensional basins. Figure 4 shows that the distribution of these basins was mainly controlled by pre-existing Variscan or earlier structures with inherited northerly, 'Malvernian' orientations; for example, the Hopton, Sandon, Western Boundary, Polesworth and Burton faults.

Three pulses of sedimentation deposited the Triassic strata that dominate the Trent valley catchment geology (Figure 6). Initially,

Figure 7. Permo-Triassic palaeovalleys excavated on a mountainous Precambrian landsurface and filled with Mercia Mudstone strata, revealed on the east face of Bardon Hill Quarry, Charnwood Forest.

major rivers flowed from the south (Warrington & Ivimey-Cook 1992), exploiting the developing extensional basins and depositing sandstones and conglomerates of the Sherwood Sandstone Group. These strata, which are major aquifers, host the famous caves of Nottingham, and form the many exposures around Nottingham University campus, visited during the Symposium. The magnitude of differential subsidence at this time is exemplified by the 760 m of sandstone present in the Knowle Basin (Powell *et al.* 2000), as opposed to the 50-150 m thickness range that is typical outside such basins.

Later in the Triassic Period, intensely arid climatic environments characterised deposition of the Mercia Mudstone Group. The presence and thickness of these strata is attributed to a more widespread phase of crustal downwarping that confined and preserved the sediments, allowing them to thicken and eventually to completely cover most of the upstanding topographical elements, such as the Precambrian mountainland of Charnwood Forest. In the latter area, the basal Triassic unconformity is spectacularly displayed in Bardon Hill Quarry (Figure 7) visited during this Symposium. It is the locus of sporadic mineralization that includes base metals (Pb-Cu-V-Mo) and, more rarely, gold and silver (King 1968). The red-coloured Mercia Mudstone strata that are so distinctive to the landscapes of the Trent catchment were also examined during the Symposium visit to the Dorket Head brickpit. They have been compared with loess-type deposits, and latterly (Jefferson *et al.* 2002) with the modern 'parna' of the south-eastern Australian desert. A complex of mainly continental environments is represented, albeit with occasional marine influences, in which were accumulated thick sequences of red-brown or rarely green-grey mudstone of aeolian to lacustrine origin, punctuated by fluvial episodes that deposited beds of green-grey dolomitic siltstone and sandstone, commonly referred to as 'skerries' because of their relative hardness and resistance to erosion. Higher in the group, evaporitic conditions are indicated by the incoming of gypsum, of local commercial importance.

The Penarth Group, of Rhaetian (latest Triassic) age represents the final phase of sedimentation. These predominantly argillaceous strata are of marginal marine facies (Swift & Martill 1999) and represent the initial deposits of a major transgression. They form a small, but conspicuous escarpment feature throughout the Trent region.

Jurassic to Cretaceous submergence of the Pangaea margin

Marine conditions persisted throughout the Trent region during this 140 million year interval. Jurassic strata of the Lias and Inferior Oolite groups are the main survivors of later Cenozoic erosion. They are disposed within a 'wolds'- type landscape of cuestas and dip-slopes on the eastern margin of the Trent catchment (Figure 2). In part, their outcrop limit determines the course of the Trent as it approaches the Humber estuary (Figure 1). The grey mudstones of the Lias Group accumulated in a generally warm, shallow, sub-tropical sea that was now established across the East Midlands Shelf. The waters deepened with time, leading to better oxygenation and a transition into hemipelagic shelf environments (Weedon 1986) that supported a diverse fauna of ammonites and bivalves. The Marlstone Rock Formation gives rise to a particularly dramatic escarpment overlooking the Vale of Belvoir, and has been a major source of ironstone and building stone. With its locally prominent cross-bedding, the unit represents one of the shallow water, regressive episodes on the East Midlands Shelf. A later regression is documented at the commencement of the Inferior Oolite Group (Hallam 2001).

Cenozoic uplift and erosion - the modern landscape emerges

Cretaceous strata probably accumulated across the whole of the Trent region during the final stages of the Pangaea shelf sea; however, little is known of their final extent or age because they were largely removed during 60 million years of Cenozoic erosion (Green *et al.* 2001). The latter study suggested at least two episodes of uplift, which are usually attributed to a combination of tectonic events: the opening of the Atlantic Ocean and compression transmitted from the Alpine Orogeny, which developed from the middle Cenozoic onwards. Recent work suggests that the Cenozoic tectonic regime was asymmetric, involving a principal axis of uplift along the western seaboard of England (Bott & Bott 2004). This produced eastward tilting, about one degree on average, that allowed erosion to etch out the scarp and dip-slope topography that characterises the 'wolds' landscape on the Jurassic and Cretaceous outcrops in the far east of the Trent region. The tilting initiated systems of east-flowing rivers, which were the main agencies for dissecting and removing the Jurassic and younger sequences (Gibbard & Lewin 2003). One of these systems was the Bytham (or 'proto-Soar') River, the sandy deposits of which indicate that it originally flowed north-eastwards through Leicester (Figure 1), along the present Soar valley and thence eastwards, along what is now the Wreake valley (Rice 1991).

It is anticipated that this Cenozoic tilting, through the geomorphological process of superimposition, would have produced a landscape dominated by eastward-draining river systems. However, while elements of such a pattern are indeed represented, for example the upper and middle Trent and Dove rivers, they are disrupted by trunk streams that follow northerly courses, exemplified by the Tame, Soar and parts of the Trent (Figure 1). The most obvious control over this deflected drainage pattern is the Triassic outcrop, with the northerly flowing streams favoured by the former sites of Triassic rifting, particularly along the Knowle, Hinckley and parts of the Needwood basins (Figure 6). This control was most probably facilitated by the reactivation of the Triassic structures with Variscan inheritance that originally

delineated the Triassic basins (Figure 4). Thus as it was being uplifted and tilted, the postulated Jurassic to Cretaceous cover was in places fractured by faults that interfered with and locally deflected the easterly-flowing, superimposed river courses. There is abundant evidence in the Trent region for such post-Triassic fault reactivation (Smith *et al.* 2005; figure 44), including displacement of the youngest-preserved (Lower Jurassic) strata; for example by the Princethorpe and Whitnash faults north of Warwick (Old *et al.* 1987).

Quaternary drainage development

The progressive northwards drift of the Eurasian Plate throughout the Cenozoic Period, acting in combination with other factors, culminated in the onset of colder climatic conditions early in the Pleistocene Period. The first major British glaciation occurred during the Anglian Quaternary Stage, about 440,000 years ago, when ice sheets covered the whole Trent basin, depositing locally thick 'superficial' sequences of glacigenic material dominated by till (boulder clay). Mapping by BGS has shown that the till deposits mantle a pre-existing topography, which includes pre-glacial valley systems such as that of the Bytham River (Rice 1991). Thus the topography revealed following the partial erosional removal of the Anglian deposits is largely inherited from the Cenozoic landscape. Since ice withdrawal, however, there have been many significant drainage reorganisations to the pre-Anglian systems. For example, the drainage in the Wreake valley (Figure 1) was reversed to its modern westwards flowing direction.

Regional isostatic rebound and superimposed glacioeustatic fluctuations, dating from the Anglian ice withdrawal, have further influenced not only landscape development, but also the nature and distribution of fluvial deposits throughout the later part of the Pleistocene and into Holocene times. Successive aggradations and incisions over this period have resulted in a 'flight' of five Trent river terraces (e.g. Posnansky 1960; Carney *et al.* 2001), each separated by a 4-7 m vertical interval. The highest and oldest terraces (Eagle Moor and Balderton terraces) have been radiometrically age-dated (Brandon & Sumbler 1991); their outcrops indicate that in pre-Ipswichian ('Wolstonian') times at least, the Trent must have flowed eastwards through the gap in the Jurassic escarpment at Lincoln (Figure 1). Its subsequent diversion northwards to the Humber estuary may be a result of the younger, Late Devensian glaciation that occurred about 30,000 to 12,000 years ago, the ice front of which would have presented a barrier to drainage around the eastern, northern and western fringes of the Trent basin. The youngest Trent terrace, the 'floodplain terrace' of Posnansky (1960), represents the valley-confined glacial outwash deposits of this latest cold stage; it is commonly thickly developed beneath the modern alluvium and is a major producer of sand and gravel, from pits such as that at Shardlow, visited during this Symposium. In Figures 1 and 6 its outcrops (named as either the Syston or Holme Pierrepont terraces) have been combined with those of the modern alluvium to provide a geological depiction of the Trent floodplain network. The mid-Pleistocene through to Holocene geomorphological and archaeological development of the Trent valley is described by Knight & Howard (2004), and in further articles of these Proceedings.

Conclusions

The long and complex geological history of the Trent region has played an important, albeit subtle role in determining its modern physiography. This article has documented the effects of major plate tectonic changes that have underpinned such a role, generating and perpetuating structures controlling geological and geomorphological processes. The most obvious legacy of this structural evolution is a plethora of 'weak' crustal zones in the form of faults, folds and cleavage belts. Many of these were initiated hundreds of millions of years ago but they have persisted through time as a result of their repeated, 'posthumous' reactivations, a process recognised by Turner (1949). By extrapolation into Cenozoic time, it is likely that inherited structure continued to be an important geomorphological influence, imparting a differential component to uplift and tilting and contributing to the wide variety of rocks, landscapes and drainage patterns seen today in the Trent catchment.

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The quarrying, use and transport of building stone in the catchment area of the River Trent

Graham Lott and Don Cameron, British Geological Survey, Keyworth, Nottingham

The Trent, and its tributaries, drain an area of *c.*7500km^2 covering parts of South Yorkshire, Humberside, Derbyshire, Nottinghamshire, Staffordshire, Leicestershire and Warwickshire (Plate 1). In its heyday the river was the M1 of the Midlands and a major routeway for transporting and distributing a wide range of products produced in the Midlands. Not only were such goods shipped locally, from village wharf to village wharf, but there was also a national and international trade, via the Humber Estuary, around the UK and across the North Sea into mainland Europe. Conversely the river and its many tributaries were, from earliest times, also an access route for both people and goods from other areas of the UK and mainland Europe (Saltzman 1967; Wood 1950; Stone 2005).

Despite many navigation problems, such as the need to trans-ship goods at shallow river sections like Shardlow, near Nottingham, there is considerable evidence of a thriving trade in the shipment of heavy goods, including many industrial minerals, along the Trent and its tributaries from earliest times. Where there were navigational problems along the rivers major engineering schemes were set up to canalize, deepen or even divert parts of the river and its tributaries (Wood 1950; Beckwith 1966; Gaunt 1975; Stevens 1992; Stone 2005). Among the goods traded along the river were alabaster from the mines at Chellaston near Derby (14th –16th century), coal from the Wollaton collieries (16th century) near Nottingham, pottery from Stoke (18th century), salt and beer from Burton-on-Trent (18th century), iron goods, including munitions from the Derby forges (17th and 18th centuries), millstones and lead from the Peak District mines (17th & 18th centuries), lime from Barrow on Soar and Crich (19th century) and granodiorite and slate from Charnwood Forest (19th century).

In the lower reaches of the river, major river ports developed, first at Torksey and later, as the size of both the trade and the river craft increased, at Gainsborough. Torksey, a sizeable town, second only to Lincoln in the area prior to the 14th century, lies on the junction linking the Trent to Lincoln and to the River Witham and the Port of Boston, via the Roman Fossdyke Canal. It appears to have gradually declined after the canal was allowed to silt up. Gainsborough has been a river port since medieval times but became much more prominent from the 16th century as a trans-shipment point where goods were generally moved from the small river craft to larger sea going vessels. Many other locations on the river and its tributaries became important distribution centres from which goods were collected for passage down river to the Humber. Bawtry on the River Idle was the major shipping point for Derbyshire lead and Sheffield cutlery for example.

The Trent Navigation with minor improvements continued to provide the main export route for heavy goods until the late 18th century when substantial changes took place following the construction of several canal links. Often sponsored by local industrial entrepreneurs these links gave Midland producers cheaper more direct access to markets in other parts of the UK. The new canals included the Chesterfield Canal (1774); Erewash Canal (1779); Nottingham Canal (1789); the Trent and Mersey Canal (1779) and the Grand Union (Junction) Canal (1805) and most soon showed a considerable trade in industrial minerals including building stone.

Geology of the Trent river catchment (Plate 1B)

The source of the River Trent lies in the steep-sided Carboniferous, Millstone Grit Group sandstone escarpments of the Biddulph area to the north of Stoke-on-Trent. The course of the river then descends southwards across the Coal Measures onto the Triassic succession of the Staffordshire plain before turning abruptly to the north-east through Burton-on-Trent. Over the rest of its course, past Nottingham, Newark, Lincoln, Gainsborough and Scunthorpe, the river's course is firmly bedded on the Triassic succession before reaching the Humber Estuary at the Trent Falls.

On this long journey the river has also gradually acquired a large number of tributaries which drain varied landscapes of Precambrian - Cambrian (River Soar - Charnwood Forest), Carboniferous (River Derwent - Derby - Nottingham coalfields), Permian (Mansfield), Triassic (Staffordshire) and Jurassic (Vale of Belvoir) rocks. In each of these areas the Trent and its tributaries have been used to transport enormous volumes of trade goods, not least of which was building and decorative stone, from production site to market place, since at least medieval times. Over the same period the river has in return acted as an access point for the importation of stone from areas well beyond the region.

The quarrying of building and decorative stone in the river catchment.

The varied building stone resources available in this area include rocks of Pre-Cambrian, Cambrian, Carboniferous, Permian, Triassic and Jurassic age. Much of this stone was quarried for local use within a few miles of the quarry sources. However, there are many other examples where, from the evidence of the stone used in local buildings, it has been transported far from its original source. The Trent and its tributaries must clearly have provided important transport route for at least part of this journey. The earliest evidence for the 'quarrying' and transport of stone along the river, dates back to Bronze Age times. Several archaeological excavations in the alluvial gravels of the Trent, over many decades, have revealed a number of well-preserved log boats dating to the period. One such boat contained several large, roughly squared sandstone blocks (Bromsgrove Sandstone Formation from the nearby Kingsmill outcrop) which is believed were probably being transported for use in the construction of small quays or fishing platforms along the river shallows at Shardlow (Knight & Howard 2004).

Quarrying and use of stone for building in the modern sense, however, probably started in some areas in Roman times. The remnants of Roman stone structures occur at several locations along the Trent valley e.g. Margidunum, near East Bridgford - Triassic Sandstone Skerry and Swithland Slate; Jewry Wall in Leicester - Charnian Slate and Triassic Dane Hills Sandstone; Ockbrook 'Villa' - Carboniferous sandstones; Mansfield Woodhouse 'Villa' - Mansfield Stone (Knight & Howard 2004).

Evidence of the gradual expansion in the quarrying of building-stone in the catchment area is first evident from the few stone buildings that still survive from Norman and Medieval times. The higher the status of a building the more likely that its construction

would be well-funded allowing better quality stone to be brought to the construction site. This is particularly true of larger buildings such as the great houses, castles, churches and monastic buildings in the area which are in general the only stone survivors from this pre-medieval period. In such buildings the best high quality ashlar block is commonly used only as facing stone and carved decorative work, while the remainder of the fabric is constructed of local rubblestone (Grace Dieu Priory, Southwell Minster, East Bridgford Church).

From the late 16th century, in contrast, surviving vernacular houses have used local stone from nearby quarries (Skerry Sandstone, Bulwell Stone, Marlstone, Plate 3I). However, by the mid 19th century the development of local canal and railway networks allowed the construction of the buildings from a mixture of locally sourced stone and stone sourced from more distant quarries. One notable example is the pervasive introduction of a new roofing material – Welsh Slate.

The rocks of each geological system cropping out in the catchment area have provided a unique mixture of stones which are perhaps best seen in the vernacular buildings of the region.

Pre-Cambrian to Cambrian

The oldest rocks in the area crop out in the rugged landscape of Charnwood Forest. Hard, intractable volcaniclastic lithologies, slates and meta-sedimentary rocks of the Pre-Cambrian (Charnian) and Cambrian are pierced by igneous intrusive bodies at Mountsorrel (granodiorite), Markfield, Groby, Croft etc. All these lithologies have been quarried and used in the local houses and churches of the Forest area to produce a unique vernacular style (Plate 2A).

Precambrian building stones

Charnwood Forest has one of the most diverse rock successions in the East Midlands area. Many of the lithologies present are properly identifiable only under the microscope but most types can, with some practice be identified in local buildings. It is possible to attribute most of the building stone lithologies encountered in and around the area to a generic 'Charnian' suite of rock types.

The Charnian rocks used as building stone exhibit a wide variety of colours, lithologies and textures from off-white to dark grey-green and purple with micaceous, fine-grained and coarse-grained textures. They have been used in building construction since Roman times and can be seen in the remnants of Ulverscroft and Grace Dieu priories built in the 12th century. More recently Mount St Bernard's Abbey (19th century, Plate 2B) and Blackbrook Reservoir (20th C) were constructed using a variety of Charnian lithologies. Characteristically these hard intractable rocks are seen in buildings as random rubble stone and are rarely shaped or sawn into blocks. These rugged, vernacular building materials and styles are also well displayed outside the area in churches in Anstey, Leicester (St Mark and St. Nicholas), Loughborough, Long Whatton and Belton and in the village housing and old school at Osgathorpe.

Lower Palaeozoic (Cambrian) rocks

Succeeding the Charnian succession are the finer-grained rocks of the Brand Group. The succession includes the hard, metamorphosed sandstones and siltstones of the Swithland Formation, best known as the source of the Swithland Slates, the focus from Roman times to the late 19th century of an important local stone industry. The slates are characteristically purple, dark grey or green-grey in colour and were widely used for roofing, wall stone and, most famously, for the production of decoratively carved headstones. They are well displayed in the roofs and walls of houses in Woodhouse Eaves and Newton Linford, but many other examples survive in surrounding villages (Plate 3I).

The main quarries were at Brand, Groby, Swithland Wood and Woodhouse Eaves, but are long abandoned and flooded. In its heyday the Swithland Quarry was worked to a depth of 180 ft (55m) and the stone blocks had to be raised to ground level by crane before splitting, sawing or polishing. Swithland roofing slates have been found at Roman sites in Leicester and Nottinghamshire (Margidunum, Car Colston). A survey published by the Geological Survey in 1860, provides some indication of the scale of the industry. Annual production from the slate quarries at Groby and Swithland Wood was 1000 and 2000 tons respectively. By comparison, annual production at the Burlington slate quarries in Cumbria was c.9900 tons, and at the Dinorwic quarries in North Wales 90,000 tons. It is easy to see why, with the development of the railways, the Swithland slate quarries quickly went into decline. The last quarry had closed by c.1888.

The use of Swithland slate for intricately lettered and carved headstones or memorial plaques, many of which survive in the churches and graveyards of Leicestershire, south Nottinghamshire and west Lincolnshire is perhaps their best-recorded legacy. Producing the flat surfaces necessary for the intricate lettering was perhaps the most time-consuming, labour-intensive and expensive aspect of the production of these grave slabs. The slate was first hand sawn, using an abrasive water / sand slurry and subsequently polished to produce the characteristic smooth surface.

The cost and difficulties of overland transport were prohibitive, consequently the Swithland slate industry used Rothley Brook to carry the slate to the navigable River Soar and then onwards to the Trent. The subsequent construction of links to the Grand Union Canal in the early 18th century opened up further markets. Consequently the slates are found as far afield as Lincolnshire, Northamptonshire, Warwickshire and Derbyshire. However, these same innovative transport developments eventually led to the end of the Swithland slate production, when the railways began to bring cheaper Welsh roof slates and headstones in to the area in the mid 19th century.

Igneous building stones

The Pre-Cambrian-Cambrian succession of Charnwood and adjacent areas was extensively affected by igneous activity both during the Pre-Cambrian and Lower Palaeozoic. Many of the resulting igneous intrusions are now exposed in the high crags of the forest and are still locally exploited for construction materials. These coarse-grained igneous rocks comprise a very varied suite of lithologies, including dark-coloured *diorites*, pink and green *granodiorites* and dark *tonalites*. The building stone industry, however, has tended in the past to use the generic trade name 'granite' for all of them, while locally they are often termed Forest Stone. Their outcrops are concentrated in two areas that are compositionally distinct. In south Charnwood the Pre-Cambrian diorites have been quarried at Groby (coarse-grained, purple and green mottled) and Markfield (granophyric textures; coarse-grained, pink and greenish-grey feldspars, with some silica and darker green ferromagneand equant. In north Charnwood the Precambrian diorites are coarse-grained but darker in colour (dark grey), than the southern Markfieldite varieties. Probably the most

readily recognised of these northern intrusive rocks is the Mountsorrel granodiorite. This Ordovician granodiorite is pink to grey in colour, coarsely crystalline and silica-rich with both pink potash and grey plagioclase feldspars.

These igneous rocks can be identified in local buildings in much of the area and commonly occur as walling stones in a mixture of other Charnian lithologies. The exception is perhaps the red Lower Palaeozoic granodiorite of the Mountsorrel quarries. Most famous, perhaps, for the production of kerbstones and setts which were exported to cities and towns across the country from the early 19th century, it was also used long before then as a local building stone. This hard and intractable stone is commonly used as large irregular rubble stone blocks in the walls and houses of older buildings in villages close to the quarries. By the late 19th century, however, steam power saws enabled large squared blocks of dark red Mountsorrel granodiorite to be cut. Many examples can be seen in churches and houses at Mountsorrel, Quorndon, Barrow-on-Soar and Hoton, and in St. Paul's Church in Leicester. The distinctive green coloration of the coarse-grained diorite of the Markfield quarries is also readily identified in the walls of buildings in and around Groby and in kerbstones throughout the Midlands area.

Carboniferous

Carboniferous rocks crop out extensively along the rugged Pennine margin of the Trent catchment and in the low-lying areas further south of the Leicester and Coventry coalfields. The south Pennine area (Derbyshire-Staffordshire) is still one of the UK's most important producers of building stone. Both the vernacular and later industrial buildings in these areas reflect the importance of local sources of building stone. In the White Peak area, the pale grey Carboniferous limestone forms the principal building stone for most houses, farmsteads and urban centres. While further north in the Dark Peak, the limestones are replaced by the brown-buff and occasionally reddened, coarse-grained, pebbly sandstones of the Carboniferous Millstone Grit and Coal Measure groups of the Derwent Valley. In this area particularly around Matlock, a large number of sandstone quarries still provide stone for a much wider UK market.

Transportation of these limestones and sandstones to a wider market has always been an issue. Very little of the limestone has found use as building stone outside the area, but as a source of crushed rock aggregate, the present quarries provide a major portion of the British industrial limestone production. However, these same limestones locally have proved to be an important source of many decorative polished limestones, of which buff Hopton Wood 'Marble', brown Derby Fossil and Ashford Black 'marble' are the best known. Hopton Wood Stone competed with Portland Stone to provide stone crosses and monuments for the dead of the two World Wars, while Ashford Black supported a popular local craft similar to the Florentine Pietra Dura stone decoration. The coarsely crinoidal Derby Fossil limestone has been used even more widely for decorative cladding in churches, offices and quite extensively in Nottingham University's buildings. It was much favoured for making decorative church fonts and pulpits (Plate 3Q).

The Carboniferous (Millstone Grit Group) sandstones in the river's source area at Biddulph and Mow Cop, in Staffordshire, have a long history of building stone quarrying, but the River Trent at this point is far too small to have been considered as a transportation route. The quarries at the Cloud produced a particularly distinctive reddened sandstone variety but most of the hard sandstones from these quarries were only used in the local area, notably in the construction of the Macclesfield Canal (1831).

Like most quarries in Derbyshire those along the Derwent Valley, between Bakewell and Matlock (e.g. Ashover Grit for Chatsworth House (1552 onwards), Duffield and Horsley Castle (the latter using the Rough Rock for Kedleston Hall (1759-1770)) were initially restricted to local usage and did not reach wider markets until first, the Erewash Canal (1778) to the Trent at Long Eaton and subsequently the Cromford Canal (1794) were completed. However, it was the development of railway links along the Derwent Valley in the early 19th century that really established the Matlock sandstone quarries as major suppliers of stone to the fast growing industrial towns and cities of the Midlands and North. As a consequence most of the principal civic buildings of Derby and Nottingham were built with sandstones from these Derbyshire quarries, the most notable being Stanton Moor and Stancliffe Darley Dale (Plate 2C). Both were favourites of Victorian architects, with the latter providing stone for the massive columnar frontage of St George's Hall at Liverpool and for the enormous, carved corinthian capitals at Leeds Town Hall.

Perhaps the one exception to this problem of access to markets was widespread distribution achieved by the millstone industry around Hathersage and Baslow. Quarried from many moorland quarries / outcrops in the Millstone Grit sandstones, the industry was particularly active during the 14th and 15th centuries. The much sought after finished stones were taken overland to Bawtry on the River Idle, and from there along the Trent and Humber and down the coast, to King's Lynn and London, for distribution to a plethora of UK and overseas markets (Polak 1987).

The Carboniferous rocks of the overlying Coal Measures Group are best known economically for their coal reserves but the group also contains a number of sandstone beds, which have been quarried extensively for local building stone. Hardwick Hall (1597) is perhaps the best example of the use of fine ashlared sandstone from quarries in the Pennine Middle Coal Measures close to the house. Older houses and churches in the coalfield area around Eastwood, Kimberley and Trowell, for example, use local Carboniferous sandstones in their walling fabric but there appears to have been no major commercial quarrying of the sandstones in this Group.

Permian

The Permian succession in the western part of the catchment can be subdivided into a lower unit of dolomitic (or magnesian) limestone (Cadeby Formation) and an upper interval in which red clays (often termed marls) and soft sandstones dominate. The Cadeby Formation, formerly known as the Lower Magnesian Limestone, forms a notable north-south trending ridge that marks the westerly edge of the main Trent catchment. These limestones are the principal source of some of Nottinghamshire and South Yorkshire's best known building stones. They were quarried extensively in the past for building stone at Bulwell, Linby, Mansfield, Bolsover, Steetley, Anston, Roche Abbey and Cadeby areas.

The Bulwell - Linby stones are distinctive yellow-brown to orange, coarsely crystalline limestone varieties both widely used in the 19th century for housing, churches, schools and factories in Nottingham(Plate 2G). The Linby quarries originally supplied stone for Newstead Abbey in medieval times and are still operational today. The use of Bulwell Stone is documented at least as

far back as the 16th century but the quarries are now closed and the area sterilized by modern developments. The characteristic feature of the Linby and Bulwell limestones is their thinly bedded nature. They do not occur in beds greater than about 0.30m in thickness and cannot therefore be considered a useful freestone for carved decoration. However, this same thinly bedded character made them important in the 16-18th centuries for the supply of large headstones, which still survive in many graveyards around Nottingham.

The Cadeby Formation limestones show great variations in bed thickness, colour and texture northwards along the course of its outcrop. At Mansfield, the formation includes two sandy limestone varieties known as the Red and White Mansfield stones (Plate 2D & E). These stones are the only building stones from Nottinghamshire to have achieved national recognition in terms of their use and distribution. They are dolomitic limestones with a high quartz sand content and are, in consequence, particularly durable. They were extremely popular with architects and builders in the 19th century and the red variety, long worked out, was popular for decorative work both locally (Castle Brewery at Newark and in many of Nottingham's Victorian buildings (Lott 2002, Plate 2C) and nationally as in the Midland Hotel, St Pancras in London. The White Mansfield Stone which was still quarried until recently, is identifiable by the presence of thin, discontinuous, green clay seams (often termed veins by the trade) and was one of the stones selected and used in the construction of the present Houses of Parliament (Lott & Richardson 1997). They have been used since at least Roman times and are best displayed locally in Southwell Minster (Plate 2E). It is also the principal building stone used in Mansfield and in several 19th century churches in north Nottingham and many surrounding villages, however, it is only rarely seen in Nottingham itself.

Further north, in quarries at Steetley (Derbyshire), Anston, Roche Abbey and Cadeby in south Yorkshire, the Cadeby Formation dolomitized limestones are commonly almost white in colour. They often retain remnants of their original coarsely peloidal or bioclastic textures and have been widely used in local buildings (Steetley Church, Roche Abbey). Only the quarries at Cadeby still produce building stone in this part of the outcrop.

Triassic

It is not until the river crosses the overlying Triassic succession, north of Stone, (Staffs) that it has gained sufficient size and energy to allow the passage of boats large enough to carry heavy and bulky materials like building stone. The meandering river course here occasionally cuts cliff-like passages through the Bromsgrove Sandstone, the principal source of local building stone. However, although there is frequent evidence of quarrying in these outcrops there is little published documentary evidence to suggest that the stone was moved by river.

The Triassic succession is subdivided into three lithologically distinct groups: the sandstone-dominated Sherwood Sandstone Group, the mudstone-dominated Mercia Mudstone Group and a thin uppermost unit, the Penarth Group which has no significance in this area as a source of building stone. The Sherwood Sandstone Group (formerly the Bunter and Keuper sandstones) is the principal source of building sandstones in the area of the Triassic outcrop. In Nottinghamshire, the lower beds are of soft red, pebbly sandstones (Nottingham Castle Sandstone Formation) and are well exposed in the cliffs below Nottingham Castle. They have not generally been worked for building stone as they are too poorly cemented to produce durable blocks of stone. However, their soft nature was exploited in other ways in the past, notably for the excavation of extensive caves for underground storage areas, particularly in the city of Nottingham.

In contrast, the upper interval of the group comprises thick-bedded, finer-grained sandstones (Bromsgrove Sandstone Formation). In the past they were a very important source of purple-red, greenish grey and occasionally white building sandstone. Large sandstone quarries / mines are found around Stafford at Sandon Park, Weston Bank, Tixall, Great Haywood, The Cliffs, Colton and Rugely. As the main course of the Trent passes into Derbyshire, riverside quarries in the Bromsgrove Sandstone are known at Bladon, Repton and Weston-on-Cliff and, in Leicestershire, at Kingsmill and Kegworth. In Nottinghamshire, the Triassic sandstones were quarried at Basford, Chilwell, Sneinton and Gedling and are still seen in local walls and a few surviving buildings in the city centre and suburbs (Plate 2D).

The Mercia Mudstone Group crops out east of Nottingham and, despite being overwhelmingly a mudstone-dominated succession, it also includes numerous thin, hard, grey, carbonate-cemented, fine sandstone beds known locally as skerry (Plate 2F & H). Skerry sandstones are known to have been quarried in pits at Hockerton, Tuxford, Laxton, Maplebeck and East Markham but its widespread use in local buildings, from Roman times well into the 20th century, suggests these sites probably reflect only a small proportion of the actual quarrying activity over the outcrop as a whole.

Also present in the Mercia Mudstone Group are beds of gypsum (calcium sulphate) and its harder more crystalline variety – alabaster. The latter form was exploited extensively in medieval times from mines at Chellaston, between Derby and Nottingham. The hard translucent, white and red and white mottled, alabaster was used extensively for exquisitely carved monumental work. As with Purbeck Marble there are few medieval churches of note in England that do not have alabaster monuments from Chellaston on display (Plate 3P). Transportation of the alabaster was initially by the local trackways but also included shipment along the Trent to Gainsborough (Wood 1950). The medieval trade became so successful that alabaster monuments were also exported into Europe.

Lower Jurassic (Lias Group)

The eastern margin of the Trent catchment is formed by a series of low limestone ridges forming the north-south Jurassic escarpment. The blocky grey, argillaceous, limestones of the Lias, crop out in the Vale of Belvoir, from Leicestershire through Nottinghamshire, to the Humber estuary. They have been widely quarried and used in the past for vernacular buildings and churches in Leicestershire and Nottinghamshire from Willoughby on the Wolds in the south to Newark and Collingham in the north (Plate 3J). Elsewhere the grey Lias limestones are commonly used as contrasting decorative courses in church walls, as at Cotgrave, East Bridgford and Radcliffe-on-Trent.

Within this Lower Jurassic succession also occur a thin sequence of highly fossiliferous, orange-brown ironstones known as the Marlstone Rock Formation. Topographically, they form a marked ridge on which Belvoir Castle (Marlstone and Lincolnshire Limestone) prominently sits. They have been extensively used locally in villages all along the outcrop. Though an attractive stone, it is generally soft and tends to have weathered rather badly.

However, it is a distinctive and essential element of the vernacular architectural assemblage of the area (Plate 3I).

Middle Jurassic (Lincolnshire Limestone Formation)

Although the limestones of the Middle Jurassic do not crop out in the catchment area of the River Trent they are very commonly seen in the buildings of the area. The limestones form a prominent ridge that is best developed at Lincoln where the cathedral, viewed from the Trent Valley to the west, dominates the skyline. The most important quarries lie to the east in Lincolnshire. These include the Lincolnshire Limestone freestone quarries at Lincoln, Ancaster and Heydour. Further south there are several important quarries around Stamford, including Ketton, Weldon, Clipsham and Barnack. These, along with many other smaller local quarries, have provided, over several centuries, a considerable amount of high quality, buff-coloured oolitic and shelly limestone used throughout Nottinghamshire and Leicestershire for building purposes (Plate 2B). The oolites are particularly well displayed in church architecture and 19th century buildings within Nottinghamshire where it has often been used in polychromatic combination with grey Lias limestones, orange-brown ironstone and the yellow to buff Bulwell, Linby or Mansfield stones (Plate 2G).

Quaternary

Much of the land surface of the catchment is mantled by a thin covering of Quaternary glacial and alluvial clays, sandstones and gravels. The large pebbles and cobbles from these fluvio-glacial sediments were frequently used as building stone where no other suitable lithologies crop out (Plate 3M).

Imported Stones

The Trent was not only a conduit for the export of stone from the principal quarrying areas along its course, but was also a route for the import of building stone. Perhaps the most interesting import into the East Midlands area from the medieval period is Purbeck Marble. Lincoln Cathedral is extensively decorated with an impressive number of dark limestone columns, dating from the 12th century. Constructed of drums of the Lower Cretaceous freshwater fossiliferous limestones from the Isle of Purbeck in Dorset, the precise route along which these stones are likely to have been carried is equivocal (Plate 3O). Alexander (1995) has suggested that some stone used in the cathedral was brought along the then navigable River Witham via the Port of Boston on the Wash. However, it is also possible that the large quantities of Purbeck Marble used may have been more easily imported, using larger river craft, via the Humber –Trent, and then brought into the city along the Roman Fossdyke canal. This trade evidently continued intermittently for some time as there are also several large grave slabs, some dating from the 14th century, of decorated Purbeck Marble in the cathedral. Other churches along the course of the Trent also contain medieval Purbeck stones. St Mary's, the Parish Church of Nottingham, has several very large Purbeck grave slabs.

Lincoln Cathedral has other imported medieval stones, notably the large marble font carved from black Carboniferous limestone procured from the Tournai region in Belgium in the c.12th Century (Plate 3N). Again the precise transportation routes are equivocal; were the Witham or the Trent waterways used? However, the presence of a second such Tournai font, at Thornton Curtis in north Lincolnshire, close to the Humber coastline, possibly suggests that the Humber – Trent route may have been more accessible.

Such stone imports have continued. In the late 17th century the construction of a new bridge over the Trent at Gainsborough was undertaken using Carboniferous Rough Rock sandstones from the Bramley Fall and Meanwood quarries in Leeds, the stone being shipped down the River Aire to the Humber and then along the Trent to the construction site.

One further use of the river system which is of interest is its part in the redistribution and recycling of 'used' stone from earlier buildings. Re-used Millstone Grit blocks, thought to have been removed from the Roman site at York, are now found in several church fabrics along the Humber-Trent (Stocker, with Everson 1990).

Conclusions

The influence of the River Trent on the natural and built landscapes can be seen both from its exposure of the many building stones which have been used to give local buildings their unique character and also from the part it has played throughout history in the movement of stone and other minerals both in and out of the region.

Although, currently, trade on the River Trent is limited, there seems little doubt that growing energy problems will eventually force a re-evalution of the possibilities of river transportation routes in the future.

Acknowledgment

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The past, present and future of 3D Geology in BGS

H Kessler and S J Mathers, British Geological Survey, Keyworth, Nottingham

Email: hke@bgs.ac.uk; sjma@bgs.ac.uk

Introduction

In its role as a national geological survey the British Geological Survey (BGS) has produced paper maps of Britain's geology at a series of scales for the past 170 years. Over time these have become more detailed with the one-inch (1:63 360) scale being the benchmark in the mid 19th Century up to today, where 1:10 000 is the scale of primary survey considered appropriate for modern needs over most of Britain's landscape. Geological maps often require another geologist to understand them fully; the surveyors' spatial ideas, models and concepts can never be properly represented in a 2D map output, and so, to-date, much knowledge has been lost to the science and to the users.

In 1815 William Smith was already addressing the need to present the third dimension of the geology as well as the surface arrangement of units. Over time, cross-section drawing became more refined, resulting in outputs such as fence diagrams, ribbon diagrams and block diagrams to reveal the 3D structure, while contoured surfaces were used to show the spatial position of individual horizons such as major unconformities or the thickness variations of units or sequences (isopach maps).

Today, nearly 200 years after Smith's first map was published, BGS has nearly finished the systematic survey of the geology of Britain at the large scale (predominantly 1:10 000) that is required for modern needs. In addition BGS has recently compiled and published all existing data as 2-D digital geological maps of Britain (DiGMapGB) at scales up to 1:50 000 (Jackson & Green, 2003).

From 2000, the next major challenge facing BGS and other national surveys has been to begin the translation of their traditional 2D geological map outputs into fully interactive 3D geological models of the subsurface.

Past 3D modelling in BGS – the long slog

In the last three decades the rapid evolution of computer processing power has enabled scientists to create 3D models of geological structures. Much of the impetus for these developments came from the hydrocarbon and metallic mineral exploration industries. First these were simple meshed surfaces, which could be visualised as perspective views, whereas today they are solid models of highly complex structural features or entire sedimentary basins. Individual geological units are now usually modelled as objects or volumes and can either be attributed for display with a multitude of applied and themed properties, or populated internally with measurements or properties using 3D pixels, or voxels.

BGS has been building geological models for about 20 years and as past research and experience has grown preferred software packages have emerged (see Smith *et al.* 2005)

At present BGS builds general deep regional models using GOCAD, a software tool particularly favoured by the oil industry, whilst a relative newcomer - Geological Survey and Investigation in 3D (GSI3D) - is used to produce detailed systematic 3D geological models of the near-surface terrains characterised by artificial ground, superficial deposits and straightforward bedrock geology.

GOCAD is being developed through a research consortium based in Nancy and is distributed through Paradigm, a major provider of information solutions for the oil and gas industry. In BGS it has to date been used mainly for geological models at national and regional 1:1 Million and 1:250 000 scales. Data used are largely from deep exploration boreholes, 2D and 3D seismic profiles, regional geophysical surveys and published national tectonic atlases.

GSI3D has emerged in BGS over the last 5 years as a result of close collaboration with Dr Hans-Georg Sobisch, a geoscientist, software programmer and proprietor of his own software company INSIGHT GmbH based in Cologne. During this time BGS was acting as a test bed for the enhanced development of the software and workflow to closely match the working methods of a national geological survey. As a result BGS scientists from all disciplines are now able to use GSI3D to produce cost-effective, detailed, systematic 3D models that incorporate all the usable data for a given area. Such models are tied to the published surface geological linework at either 1:10 000 or 1: 50 000 scale and have the advantage, in the digital age, of being dynamic - capable of instant revision as soon as geological knowledge increases or new data become available.

Armed with these two software tools BGS is now embarking, through its new National Geoscience Framework programme, on a campaign to systematically build 3D models, at the four principal resolutions mentioned above. These models will be constructed across the entire country to standards and best practices developed from the last 5 years of research into systems and methods for 3D modelling. The products, known collectively as LithoFrame are described more fully on the BGS website. http://www.bgs.ac.uk/3d.

These LithoFrame models will be structured and attributed to meet the needs of a wide range of applied users, and ultimately, may take the place of the traditional geological map. However, this will only happen if the models are produced on a national scale, at realistic costs, and are made available and accessible to the user community.

Tools for the job, GSI3D and the Subsurface Viewer

In this article we will focus on the contribution GSI3D as a software and methodology has made to the progress of geological modelling in BGS.

GSI3D was built with geological surveyors, their working environment and culture in mind. It has resulted in an intuitive, user-friendly working package that has gained widespread acceptance throughout BGS.

The software is programmed in JAVA, is very light-weight and can be run on any standard operating system. Its file import and export formats are open and extensible, and the main model file is written in Extensible Markup Language (XML). The software is directly compatible with GIS systems and other 3D packages such as GOCAD.

GSI3D works with the principal components of any geological survey: a terrain model, mapped geological linework, borehole and these datasets enable the geologist to construct regularly spaced intersecting cross sections by correlating between boreholes and the outcrops-subcrops of units to produce a geological fence diagram of the area (Plate 4. C (colour centre spread)). Mathematical interpolation between the nodes along the sections and the limits of the units (outcrop plus subcrop) produces a solid model (Plate 4. E) comprised of a series of stacked triangulated objects corresponding to each of the geological units present (Hinze *et al.* 1999, Sobisch 2000, Kessler & Mathers 2004).

In addition to the GSI3D modelling package, a stand-alone viewer is also available for the visualisation and simple analysis of geological models constructed using GSI3D and other software packages. The Subsurface Viewer (© INSIGHT) provides a decision support system for users to resolve their problems based on the best available 3D understanding of the geology.

The analytical functionality at present allows the user to drill synthetic boreholes at any point, construct synthetic sections along specified lines or waypoints, slice the model horizontally at any required OD level, to strip off deposits from the model to produce uncovered models or to display only selected geological units. Individual model units can also be separated in 'exploded' views and enhanced 3D visualisation is possible using anaglyph images. Individual surfaces (tops, bases) can also be contoured at any desired interval. In summary the model cube can be sliced and diced at will to assess the geology. Plate 4. F-H give examples of the different views and analytical functions enabled in the Subsurface Viewer

On www.bgs.ac.uk/free a sample download of a small 3D model from the Thurrock area in East London is available along with a user manual.

The need for, and benefits of, the added dimension

Models have a wide range of applications; they are suitable for interrogation using GIS-based analytical tools to produce thematic and bespoke outputs. These geological models are generic rather than themed and so have a thousand and one potential uses and users. (Kessler *et al.* 2005)

Here we mention a few possibilities – such as enabling the thickness and volumes of aggregate resources or mineral deposits and their overburden to be contoured, and so derive thickness ratios to define cut-off points for exploration or extraction. For the hydrogeologist the combination of all impermeable layers in the stacked model can, for example, produce maps of total aquitard thickness and the degree of aquifer protection, so useful in groundwater recharge, pathway and pollution studies. Furthermore interrogation of the model at any given point will provide the user with an automated borehole prognosis for the site. Similarly, a vertical geological section can be generated along any specified course through the model for use in linear route planning or tunneling.

The most important beneficiaries of this step change in delivery of geological information will be the general public and in particular geoscience students and teachers. We envisage 3D models as shown in Plate 4E will become much more educationally informative than their forerunners … geological maps.

To-date the main commissioners of BGS-built near-surface models have been:

- Local authorities such as Glasgow City Council wanting to examine ground conditions and inform planning decisions on proposed development.
- Archaeological services such as those provided by the Museum of London and county heritage departments.
- Water companies including Yorkshire and Anglian Water to help with issues such as wetland management and pollutant pathways.
- The Environment Agency and their consultants are the biggest single customers to-date for models, using them to help resolve issues of catchment management, aquifer protection and recharge, numerical modelling and flood protection.

We applaud the vision of these varied organisations and the impetus they have given to the development of a geological modelling capability at BGS.

A vision for the future

To-date the emphasis in BGS has been on the development of model construction methods and the definition of specifications for standard models. As the availability of models increases their potential to contribute to the understanding of the geological evolution of individual areas and whole regions will become more apparent. Just as hydrocarbon models have contributed significantly to the understanding of basin evolution and structure, the more detailed near-surface models will contribute increasingly to the following areas of geoscience:

- River terrace chronology and floodplain evolution
- Archaeological preservation potential and land use change
- Soil science – spatial modelling of horizons and water tables
- Quaternary science – e.g. understanding glacial history
- Palaeoenvironmental reconstructions and landscape evolution

The modelling process described in this article leads to the building of essentially lithostratigraphic models; in this respect they mimic the geological map. These models form the building blocks of a geological survey, the LithoFrames. The real benefit of the models to the applied users appears when models are attributed with measured properties such as porosity or strength.

To fulfil the BGS mission of a systematic nationwide survey of the 3D geology, the BGS will increasingly work in partnership with government and industry. The BGS relies heavily on data from external sources such as ground investigations as well as maps and plans from construction. Business-to-business solutions with end users and common data exchange formats based on open standards will propagate the exchange of new data and, in return, delivery of updated models will add considerably to the value of ground investigation data collected by industry.

Conclusion

Geology is an inherently three dimensional science, but the portrayal and communication of the geologists' outputs was hampered for over a century and a half by the two dimensional nature of media such as paper and later GIS systems.

A good indication of the demand for the real 3rd dimension has been the exponential growth of commissions from government

agencies and industrial partners for models to provide real solutions for real-life issues.

What we have witnessed in the past few exciting years in BGS is only the beginning of a paradigm shift in the way in which the geological sciences are communicated to the whole population: the old adage *a picture paints a thousand words* springs readily to mind!

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Book reviews

Basin Analysis: Principles and Applications (2nd Ed.), by P A Allen & J R Allen, 2004, Blackwell Publishing, 549pp, £37.50 paperback, ISBN 0632052074.

Since the publication of the first edition of this book in 1990, there have been numerous changes in basin analysis in terms of data, technology and new concepts. The Allens set out to take account of these developments while maintaining the structure of the original text.

The book is logically separated into four distinct parts covering the themes of tectonic environment; the mechanics of basin formation; basin fill and stratigraphy; and the application to petroleum play assessment. Part one successfully describes the relationship of sedimentary basins to their tectonic setting. The explanation of the various mechanisms of basin formation is split into two main parts. Lithospheric stretching unifies the suite of basins produced by intracontinental sags, rifts, failed rifts and passive continental margins. Basins due to flexure are those resulting from the application of an external force on the lithosphere such as ocean trenches and foreland basins. The chapter on strike- slip associated basins is, at first sight anomalously placed, coming after a chapter on mantle dynamics, however, it does sit logically alone, as the type of basin associated with strike-slip deformation is generally smaller and more complex compared to the other types. The sediment routing system is fully analysed and explained, taking us from pristine rock, along the variety of routes to basin fill involving sediment liberation, transport and deposition. This chapter takes a look at a global view of sediment yields and deposition while basin stratigraphy gives us a primer on concepts of process stratigraphy through to the definition and recognition of stratigraphic cycles. I found the explanation of system tracts particularly easy to follow and would have found it of great assistance when studying S338. Once sediment is deposited it undergoes a variety of changes, not least the loss of porosity. The changes can be determined by a geohistory analysis, which allows the production of a curve for subsidence and sediment accumulation through time – allowing comparisons between different sections to be made. In a similar manner an understanding of the analysis of the thermal history of a section leads us through to the final part of the book, which examines the development of the petroleum concept, which brings us to the basic reason for basin analysis.

With clear, easily understood diagrams as well as a well-structured format, this book is a useful asset for its intended audience of advanced undergraduates, graduate students and professional Earth scientists. Complex mathematics is separately boxed and practical examples with solutions are provided on web pages at ETH Zurich, although I have not had an opportunity to try them out. Basin Analysis is an up-to-date treatment of the subject and a worthwhile addition to any Earth scientist's bookshelf.

Mike Hermolle, BSc (Hons) NatSci (Open)

Introduction to Organic Geochemistry (2nd Ed.) by Steve Killops & Vanessa Killops, 2005 , Blackwell Publishing, 393 pp, £29.99 (paperback), ISBN 0632065044.

Vanessa Killops is a geologist and organic geochemist and, besides his wide experience as a lecturer in organic geochemistry Steve Killops is also an OU tutor based in SE Cornwall who currently teaches S269, S339 and S369. His and Vanessa's book has its origins in an attempt to gather together the basics of this rapidly expanding subject area between one set of covers in order to help undergraduates and post-graduates following courses where this is a component part.

The 1993 original concentrated very much, in keeping with the spirit of the time, on areas related to petroleum exploration. This new edition takes a much wider, Earth-systems-related, viewpoint: it considers the chemical transformations of biological and manmade organic matter in general and covers environmental aspects, including environmental change during Earth's history. This change of focus is one that we have seen paralleled in the OU when S338 was replaced by S369. Analytical techniques are not covered although suitable texts are recommended.

The text assumes no prior specialist knowledge and the authors use a technique that will be familiar to OU students: information boxes that explain relevant subjects at appropriate places. For example the first chapter Carbon, the Earth and Life includes boxes on sediments, Earth structure, stable isotopes, comets, oxidation and reduction and so on. This saves the reader wading through material with which they are already familiar and, since the appropriate page numbers are underlined in the index, can be quickly referred to as needed.

Other chapters consider the chemical composition and the production, preservation and degradation of organic matter; the long-term fate of organic matter in the geosphere; chemical stratigraphic tools and concepts; the carbon cycle and climate and anthropogenic carbon and the environment.

My own knowledge of organic chemistry is, apart from a little picked up in S101/2/3 and information on hydrocarbons from S238 and S338, fairly minimal but the more I browsed through this book the more engrossed I became in the subject – did you know for example, that isomerization reactions in amino acids can help to unravel the thermal history of sediments – with potential use in studying glacial and interglacial sequences in the Quaternary?

Whilst the 2nd edition is still useful for petroleum geochemists, its much wider scope means that it is now a valuable text for a broad spectrum of Earth science students: it would be excellent additional reading for a student on any of the three strands in the OU Geosciences programme who is interested in knowing more about organic geochemistry.

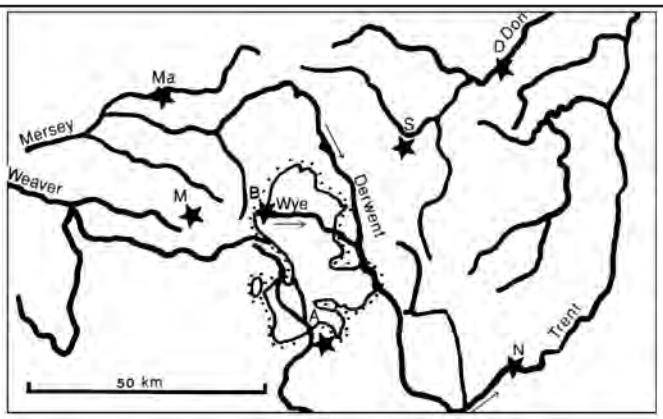
Linda Fowler (OU graduate, tutor)

Hydrogeology of the Wye Catchment, Derbyshire

Vanessa J Banks & D J Lowe, British Geological Survey, Keyworth, Nottingham

Introduction and hydrological setting

Tóth (1963) has shown that groundwater can be considered in terms of local, intermediate and regional flow systems. The theme of the Symposium being the Trent Valley, the focus of this contribution is the regional hydrogeological setting of the River Wye, Derbyshire. The research and findings that are presented comprise an aspect of work carried out during doctoral research at the University of Huddersfield. The results are derived from: research carried out by the authors; an extensive literature review; and from archives of previous work carried out by the Limestone Research Group. Although the key aim of the research was to investigate human impacts on the hydrogeology of the Wye catchment, this could only be achieved by deriving conceptual models for the karst hydrogeology associated with the Wye catchment and its hydrogeological setting. A secondary aim of the research was to reassess earlier work in the context of modern developments in the understanding of karst hydrogeology.The hydrological setting of the River Wye, as a tributary of the River Derwent, which in turn forms a tributary of the River Trent, is shown in Figure 1. A conceptual model of the regional hydrogeology of the White Peak (area of exposed limestone of the Derbyshire Dome) has developed from consideration of: the tectonic setting of the White Peak; its geological and structural context; karst hydrogeological processes; and the human impacts and their contribution to their understanding of the regional hydrogeology. A brief overview of each of these aspects and their contribution to the model is presented below.

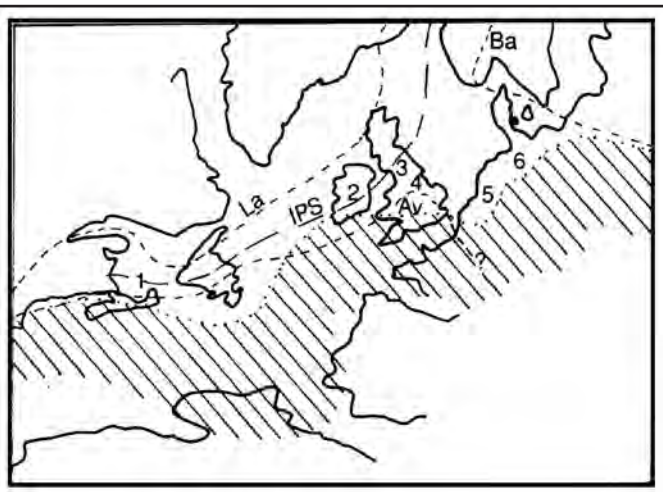


Key: Locations: Ma Manchester; M Macclesfield; B Buxton; S Sheffield; D Doncaster; A Ashbourne; N Nottingham. Dinantian limestone is outlined, with dots on outside of outcrop. Principal rivers named.

Figure 1. Hydrological setting of the Rivers Wye and Derwent as tributaries of the River Trent.

Geology: tectonic setting, lithostratigraphy and structure

A postulated series of suspected terranes has been identified in the Precambrian and Lower Palaeozoic foundations of the British Isles (Cope *et al.* 1992). In this setting, the Derbyshire Dome lies on the northern edge of the Midland Platform (Figure 2). It has been speculated (Pharaoh *et al.* 1987) that the area to the east of the Midland Platform was controlled by the evolution of a subduction zone, comparable with that of the more extensively documented Welsh Basin. As the Iapetus Ocean closed the effects of the Caledonian Orogeny were deflected around the Avalonian Terrane, imposing a northwest to southeast-trending structural grain on the basement rocks in the area of the Derbyshire Dome.



Key: Plate names: Av = Avalonia; La = Laurentia; Ba = Baltica (plate collisions occurred during Late Silurian to Early Devonian times); IPS = Iapetus suture; Hatched area denotes the Variscan foreland during the Late Devonian to Tournaisian. Sedimentary basins forming in front of this include:

1 North Appalachians
2 Central Ireland
3 Craven
4 East Midland (Derbyshire Dome)
5 Dutch
6 Northwest German

Figure 2. Tectonic setting of the Derbyshire Dome (adapted from Smith & Smith 1989).

During the late Devonian, closure of the Rheic Ocean (or proto-Tethys) was associated with the northward movement of Gondwanaland towards Laurentia and the formation of a northerly-dipping subduction zone beneath the Midlands craton as Pangea was created. The resulting Variscan deformation front moved northwards. Leeder (1988) associated this with a period of back-arc basin formation and subsidence, followed by thermal subsidence and foreland basin development during the Silesian, when the Derbyshire Dome was subject to north–south-trending extensional stresses. In this setting Leeder (1988) postulated localized melting of the asthenosphere, which gave rise to widespread basaltic vulcanicity. The evidence suggests that north–south extension was accommodated in the pre-existing structural grain.

Smith and Smith (1989) and Quirk (1993) suggest that the formation of the North Sea during the Permian and Mesozoic was associated with easterly tilting. Palaeogene uplift, thought to be associated with igneous underplating (Holdsworth *et al.* 2000) is attributed to the opening of the Atlantic. Neogene basin movements are attributed to the Alpine Orogeny.

During the Carboniferous, shelf carbonates, which comprised shallowing upward sequences, were laid down on an easterly dipping platform, within which two basins, the Ashford Basin and the Stanton Basin developed. The depositional environment has been interpreted by Aitkenhead *et al.* (1985) as one of a shallow carbonate shelf subject to interplay between eustatic and tectonic controls on sedimentation. Table 1 provides a summary of the formations of the carbonate platform and Figure 3 gives an indication of the distribution of the formations.

Table 1: Formations of the Derbyshire Dome (terminology derived from Waters *et al.* 2006).

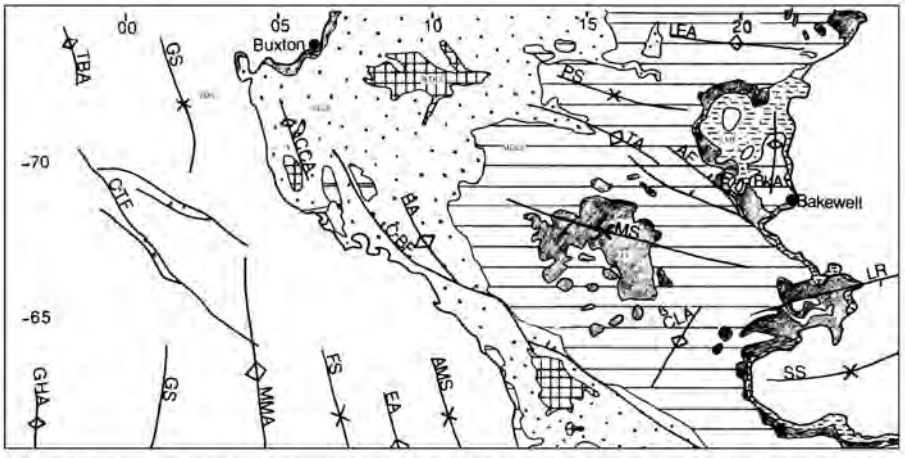
Regional Stage	Formation	Member
Brigantian	Widmerpool Eyam Limestone Monsal Dale Limestone	
Asbian	Bee Low Limestone	Miller's Dale Limestone Chee Tor Limestone
Holkerian	Woo Dale Limestone	
Arundian		
Chadian		
Ivorian		

The Woo Dale Limestone Formation comprises a sequence of open shelf limestones, overlain by finer-grained peritidal deposits, which migrated from north to south across the shelf. The peritidal deposits are overlain by restricted lagoon (packstones and grainstones) deposits. Limestones of the Asbian and Brigantian stages have been shown to be cyclic, with each bed showing evidence of progressive shallowing (regressive sequences). Typically a cycle of the pale facies of the Monsal Dale Limestone comprises basal coarse bioclastic grainstone/packstone grading to bioturbated, bioclastic, packstone/wackestone with coral bands, grading to fine-grained, sorted bioclast peloid grainstones, locally capped by wackestones and fenestrae (Gutteridge 1989). Walkden (1974) has shown that the upper parts of beds show evidence of emergence, including calcrete textures and palaeokarstic surfaces.

Asbian and Brigantian volcanic rocks are interbedded with the shelf limestones. These have all been interpreted (Aitkenhead *et al.* 1985) as penecontemporaneous lavas or tuffs. They are predominantly subaerial deposits of vesicular olivine basalt (Aitkenhead *et al.* 1985), characteristic of continental rifting. Submarine deposits have been identified in boreholes and are associated with thicker volcanic sequences (Aitkenhead *et al.* 1985). In addition to lavas and tuffs, the limestones are commonly interbedded with thin potassium bentonite clay horizons, interpreted as layers of weathered volcanic ash, known locally as clay wayboards, which rest on palaeokarstic surfaces (Walkden 1974).

There are also dolerite sills e.g. at Buxton (Waterswallows) and dykes, e.g. in Great Rocks Dale, near Peak Forest. A vent neck and associated dykes have been identified at Calton Hill, above Taddington and others have been identified including Peter's Dale, Monks Dale, and Castleton (SK 211670; SK 207684; SK 143826 respectively).

Reef limestones occur in both the shelf and off-shelf facies and in a range of stratigraphical horizons. Waulsortian-type mud mounds are restricted to the periphery of the White Peak. Asbian to Brigantian reefs, which do occur in the area, are most commonly referred to as knoll reefs, flat reefs and apron reefs, "build-ups", or "lime mud build-ups". The different types of reef have common lithological features, comprising poorly-bedded pale to mid grey micritic limestones with dips reflecting the original slopes of the reef flanks at progressive growth stages. The detailed structure of the reefs appears to have varied. Reefs fringing the Woo Dale Limestone platform were formed almost entirely of micritic mud; others had a micritic core surrounded by crinoidal flanks (Gutteridge 1983).



Key: Structures - AF Arrock Fault; AMS Archford Moor Syncline; BA Brierlow Anticline; BkA Bakewell Anticline; C-BF Cronkston-Bonsall Fault; CCA Countess Cliff Anticline; CLA Calling Low Anticline; C-TF Cut-Thorn Fault; FS Fernyford Syncline; GS Goyt Syncline; GHA Gun Hill Anticline; LEA Longstone Edge Anticline; LR Long Rake; MMA Mixon Morridge Anticline; MS Monyash Syncline; PS Priestcliffe Syncline; SS Stanton Syncline; TA Taddington Anticline; TBA Todd Brook Anticline.

Formations: –

BLLF Bee Low Limestone

ELF Eyam Limestone

MDLF Monsal Dale Limestone

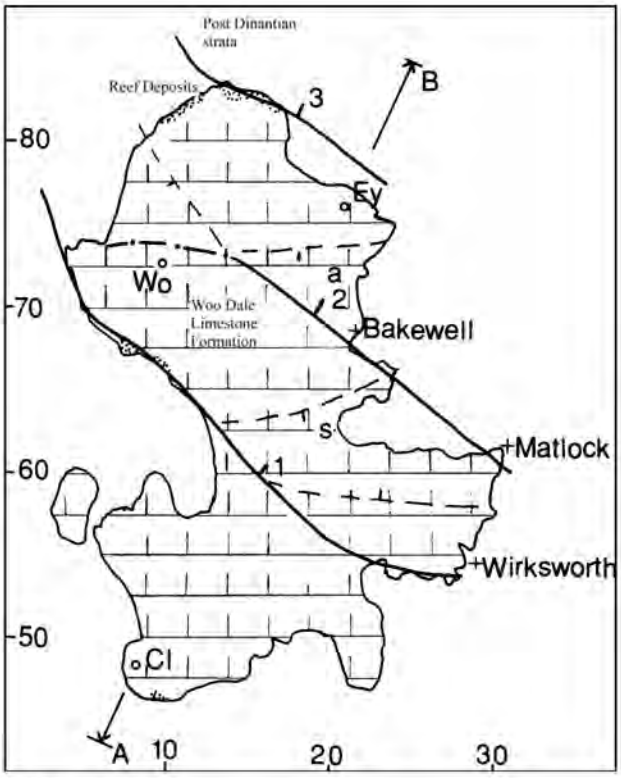
PDR Post Dinantian Rocks

WDLF Woo Dale Limestone

LMF Widnerpool

Figure 3. Principal structures and formations of the Wye catchment.

Namurian and Westphalian sedimentation largely comprised deltaic, Millstone Grit Group, sequences overlain by the Pennine Coal Measures that capped the limestone and filled deep basins (troughs or gulfs), such as the Edale and Widmerpool gulfs, adjacent to the White Peak. Following sedimentation, burial and high local heat flow provided the appropriate conditions for mineralization, with a source of metals readily available in the shale-filled gulfs. Initially, with temperatures of approximately 80 to 125˚C, an early phase of fluoride and hydrocarbons was mobilised from the adjacent troughs. Deeper burial mobilised a second phase of hydrocarbons, associated with the release of iron- and manganese-rich mineralizing fluids. Subsequently the mineralizing processes reached a maximum activity and this is associated with an increase in the salinity of the mineralizing fluids. Temperatures during this stage reached a maximum of approximately 200˚C and this is the only phase of mineralization that was asso-



Key:

Cl	Caldon Low Borehole	1	Cronkston-Bonsall Fault (Cornwell and Walker, 1989; Gawthorpe et al., 1989)
Ey	Eyam Borehole		
Wo	Woo Dale Borehole		
EG	Edale Gulf	2	Bakewell Fault (Smith et al., 1985)
a	Ashford Basin	3	Edale Fault (Fraser and Gawthorpe, 2003)
s	Stanton Basin		

Figure 4: Postulated basement structure of the White Peak (adapted from Smith *et al.* 1985).

ciated with significant barium precipitation. Much of the evidence for this comes from studies of the mineral vein cements (Hollis & Walkden 1996). The mineral deposits have been subject to a number of phases of exploitation from at least Roman times to the present. Historically, the most valuable product was lead; more recently value has been found in the gangue deposits (fluorite, barite and calcite). Evidence of post-Dinantian sedimentation is largely restricted to the Brassington Formation (Walsh *et al.* 1972), which is a Tertiary (Miocene to Pliocene) terrestrial deposit, associated with the area immediately to the north of the Cronkston-Bonsall Fault (Figure 4). It is thought that the sediment was derived from the receding Triassic margin and laid down by a braided river system (Ford 1977). Glacial deposits are of limited extent, as the Devensian ice sheet did not extend over the area. However, there are extensive deposits of head and loess.

Key features of the structure are indicated on Figure 3. The northwest to southeast structural grain referred to above is represented in the area of the Taddington Anticline. A number of the northwest to southeast-trending faults are coincident with apparent folds and are considered to be growth faults (Aitkenhead *et al.* 1985). These tensional faults, which were active during sedimentation, not only influenced the depositional environment but also, subsequently, exerted some control on weathering patterns and hence upon the development of surface drainage in the area. East to west-trending faults can also be identified in the area. These are likely to be compressional faults, associated with the northerly migration of the Variscan front as Africa docked against Europe. Stratigraphical responses to the stress history have influenced karst evolution, which is important in terms of recharge and flow path mechanisms acting in the limestone aquifer.

Comparison of the findings of the Woo Dale Borehole (Cope 1973), which encountered basement rocks in the order of 600m below ground level, and the Eyam Borehole (Dunham 1973 and Figure 5), which encountered basement rocks about 1400m below ground level suggests that the Dinantian sediments were laid down on an irregular basement, thus confirming the importance of the structural grain imposed on the basement rocks. An interpretation is shown on Figures 4 and 5.

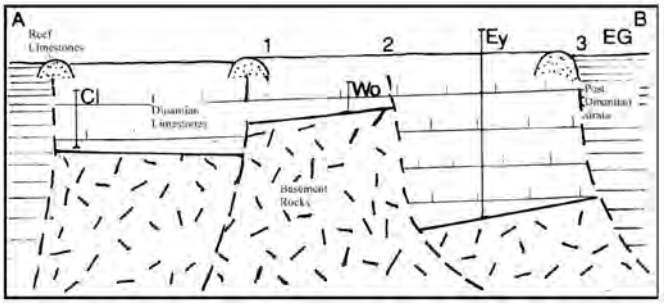


Figure 5: Schematic basement profile along line of section indicated on Figure 4 (adapted from Smith *et al.* 1985).

Karst hydrogeological processes: water table, thermal springs and groundwater chemistry

Karst aquifers exhibit a triple porosity comprising fractures (bedding planes, faults and joints) separating matrix blocks and interconnected by conduits (Worthington & Smart 2004). Much of the permeability is derived from the effects of limestone dissolution, with the resultant formation of dendritic underground drainage networks. Identification of the water table in karst aquifers has been the subject of considerable debate, as described by Lowe (1992). Therefore, in order to understand the hydrogeology of the White Peak, it was considered that it was first necessary to establish the groundwater base-level for the aquifer. Initially it was assumed that this would be the River Wye. However the situation is complicated by the presence of thermal springs, some of which resurge in the Derwent Valley, which suggests that deeper flow paths must exist within the limestone aquifer. Recognition of this factor prompted an investigation of the distribution and nature of the thermal springs, as summarised on Figure 6. It is apparent from Figure 6 that most of the thermal springs are close to the periphery of the limestone outcrop. Additionally, many of the thermal springs are also closely associated with dominant faults; for example the fissure-fed nature of the thermal spring at Buxton was described by Barker *et al.* (2000).

Gunn *et al.* (in press) report the findings of recent isotopic investigations carried out on the White Peak thermal waters. A radiogenic source of strontium was identified in the Buxton (St Anne's Well) thermal water, seeming to confirm the hypothesis that the flow paths associated with the thermal springs are at, or close to the contact between the limestones and the basement rocks. Furthermore, Gunn *et al.* (in press) suggest that, whereas it has previously been assumed that the groundwater feeding the Buxton thermal rising is derived from limestone, examination of the spring chemistry suggests that it is not a typical limestone groundwater. In an examination of the

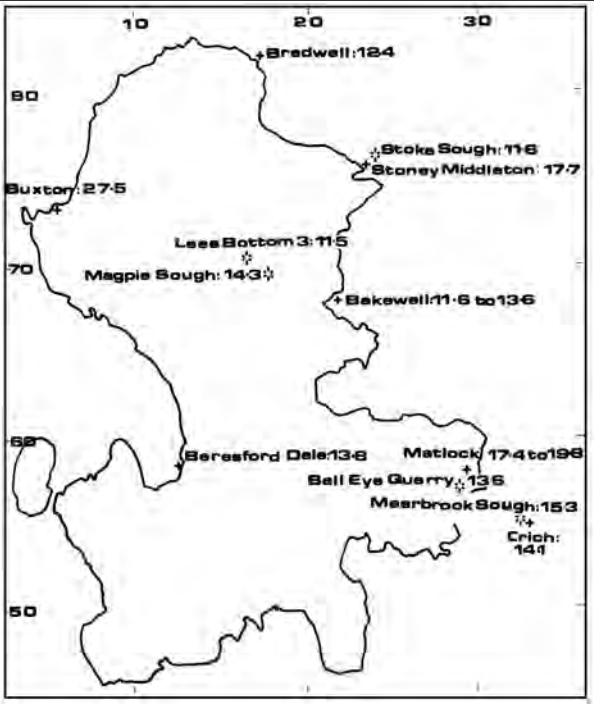
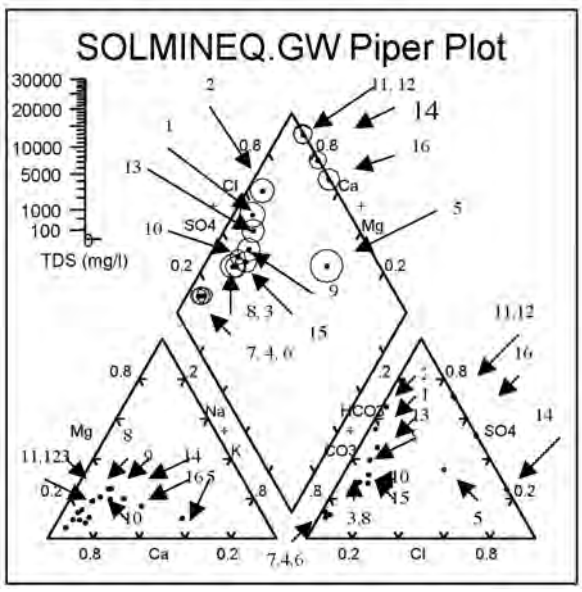


Figure 6: Distribution and temperatures of the thermal springs of the White Peak.

depth of conduit flow in carbonate aquifers, Worthington (2001) reconsidered empirical data derived from structural and flow characteristics of nineteen caves from across the world whose flow path length, bedding dip and depth of flow beneath the water table are well documented. Worthington's interest was in supporting the concept that the dissolutional activity associated with the evolution of deep flow paths is facilitated by the decreased viscosity of the circulating fluid at depth, as a consequence of its heating. He established the following empirical relationship: $D = 0.18 (L. \Theta)^{0.79}$ where, D is the mean depth of flow (m) below the water table; Θ is the sine of the dip (˚) and L is the flow path length (m). Assuming a geothermal gradient of 15˚C/km for the limestone of the White Peak and assuming a background spring temperature of 8.5˚C, it is possible to calculate the theoretical minimum depth of flow associated with each of the thermal springs shown on Figure 6. This is interpreted as a minimum flow depth value because it is known that there is some mixing of surface water with the thermal water close to the ground surface. By changing the subject of the equation derived by Worthington (2001) and using the calculated flow depths, an empirical estimate of the flow path lengths associated with each of the thermal springs can be calculated. In the case of the Peak District the calculated flow path length estimates are in the range 20 to 40km.

Two alternative conclusions could be drawn from these results. Firstly, given the easterly and southeasterly hydraulic gradient across this part of the White Peak, they provide supporting evidence for the derivation of the Buxton groundwater from outside the area of the Derbyshire Dome. Indeed, in conjunction with evidence derived from an examination of the structure of the Namurian strata on the western side of the Derbyshire Dome (Stevenson & Gaunt 1971), they appear to support the authors' view that the faulted ground on the eastern side of the Todd Brook Anticline constitutes the recharge zone. Alternatively, the conclusion is that perhaps the Derbyshire Dome is not adequately represented by the available empirical data and that additional factors have influenced the establishment of deep flow paths. Not least among these factors is the possible occurrence of halite deposits in inter-block basins, associated with early Tournaisian deposits, as identified in the Eyam Borehole (Dunham 1973) and Hathern No.1 Borehole (Carney *et al.* 2001). However, based on the evidence of groundwater geochemistry, Downing *et al.* (1987) describe thermal water in boreholes at Eakring (Nottinghamshire) that appears to be derived from the Peak District limestone. This provides an additional indication of the potential existence of long flow paths associated with groundwater underflow (the flow paths that pass beneath the local and intermediate basin to target the regional flow system). As the calculated values are empirically derived they cannot be relied upon as accurate estimates of flow path lengths, but rather they provide supportive evidence for the conceptual model presented below.

Worthington and Ford (1995) noted that the sulphate concentration in the Matlock thermal waters is greater than that in the other thermal springs and is associated with the springs that exhibit the greatest thermal flux, suggesting that this represents the underflow from the aquifer. In considering the descriptions of the formations presented previously, it is clear that one source of the sulphate is anhydrite that would be expected to occur within the peritidal deposits of the Woo Dale Limestone Formation. However, another potentially more significant source of sulphate is indicated by consideration of the Dinantian deposits to the north and south of this area, where Dunham (1973) and Carney *et al.* (2001) have identified anhydrite deposits (the Middleton Dale Anhydrite Formation and Hathern Formation respectively) towards the base of the limestone. It follows from these observations that the karstic development that supports at least some of the deep flow paths in the limestone is associated with anhydrite dissolution.



Key: 1 Bakewell British Legion; 2 Bakewell Recreation Ground; 3 Ball Eye Quarry; 4 Beresford Spring; 5 Bradwell Thermal; 6 Lees Bottom 3; 7 Magpie Sough; 8 Matlock East Bank Rising; 9 Matlock Fountain Bath; 10 Matlock New Bath Hotel; 11 Meerbrook Sough - 1; 12 Meerbrook Sough – 2; 13 Ridgeway Sough; 14 St Anne's, Buxton; 15 Stoke Sough; 16 Stoney Middleton

Figure 7: Piper Plot of thermal spring water chemistry.

The concept of a groundwater source area beyond the limestone catchment for the Buxton thermal spring is supported by Edmunds (1971) and Gunn *et al.* (in press) spring chemistry data (Figure 7). The Buxton thermal water plots (Figure 7) as calcium chloride water, whereas typical limestone water is calcium bicarbonate water, as encountered in the Lees Bottom thermal spring. The plot also confirms the significance of sulphate in the Matlock thermal springs, Stoney Middleton thermal and Meerbrook Sough waters, which comprise calcium sulphate groundwaters. Bradwell Spring comprises sodium chloride-rich water.

Human impacts on the hydrogeology and their contribution to the understanding of the regional hydrogeology

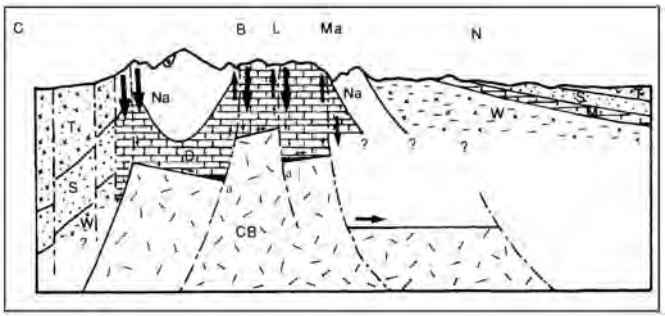
Reference to mineralization has been made previously. Mining in the Peak District dates from Roman times and possibly earlier, on the evidence of inscribed Roman lead ingots (pigs) and finds in Early Bronze Age barrows (Ford & Rieuwerts 2000). At the time of Domesday there were seven plumbariae in Derbyshire, including one at Ashford and one at Bakewell. Minerals that were mined included: galena, sphalerite, cerussite, smithsonite, fluorite, barite and calcite; Ford *et al.* (1993) provide a more comprehensive list. Early interest was primarily in the lead minerals. Exploitation was initially from surface workings but, as the shallower parts of many of the veins became exhausted, deeper mining was essential to maintain productivity. This was carried out via shafts, the earliest of which were bell pits.

Drainage of workings was a very significant factor in the progress of lead mining. By the seventeenth century most of the lead had been worked to the depth of the local "water-table" (commonly a perched groundwater level) and dewatering became necessary. Initially this was achieved by use of rag and chain pumps or by directing groundwater into natural cavities (Rieuwerts 1980), but the practice of sough driving (excavation of adits to drain groundwater to valleys) commenced at about the same time. Initially, soughs were local features but, as the need arose to achieve greater depths of dewatering, they were constructed at deeper levels, and the soughs became longer and their engineering became more demanding. Most of the soughs were drained towards the east i.e. down the natural hydraulic gradient, and thus their influence is to reinforce the easterly hydraulic gradient of the area.

A major contribution to the understanding of the regional hydrogeology of the Peak District was provided by research carried out at Magpie Mine (Willies *et al.* 1980). Magpie Sough, one of the major soughs of the White Peak, normally discharges 325 to 400 l/s to the River Wye, and was driven a distance of about 1800m from the river to the mine. In 1881, when the soughers broke into Townhead Vein, a head of water in the order of 33m was discharged into the sough, and springs within the zone of influence of the sough are reported to have dried up (Willies *et al.* 1980). This observation is relative, in that some of the springs still discharge small quantities of water at some times of the year, but they once formed a significant source of potable water. The extent and significance of this impact contrast with the relatively localized impact of the shallower soughs, and it is considered that this reflects the important role of the Arrock Fault, a basement growth fault associated with the Taddington Anticline, as a zone of substantial vertical flow and groundwater storage.

Conclusions and conceptual model

Evidence suggests that the White Peak receives a component of allogenic recharge, via deep groundwater flow paths, from Namurian strata on the western side of the Derbyshire Dome (Todd Brook Anticline) the evidence for which comes from the chemistry of the thermal spring water at St Anne's Well, Buxton (Gunn *et al.* in press). In the northern part of the White Peak the hydraulic gradient is towards the east, whereas to the south of the Wye the hydraulic gradient has a more southeasterly component. Thus, it would appear that the regional flow paths are influenced by fault-block geometry. Supporting evidence for this comes from the consideration of thermal flux and groundwater chemistry. Although several deep flow paths now feed thermal springs on the eastern side of the Derbyshire Dome, for example at Matlock and Stoney Middleton, it is suspected that some thermal water also enters the River Derwent, where elevated temperatures have long been recognised (e.g. Farey 1811). Further, it can be hypothesised that deep underflow paths extend beyond the River Derwent to target the River Trent, as indicated by the thermal water encountered in the Eakring boreholes (Downing *et al.* 1987). Evidence from Magpie Sough suggests that basement faults form zones of vertical groundwater movement and storage, and where soughs penetrate these faults there is significant impact on groundwater levels. These observations and conclusions enable construction of a conceptual model (Figure 8) for underflow associated with the White Peak.



Key: Localities: C Cheshire Basin; B Buxton; L Lees Bottom; Ma Matlock; N Nottingham
Lithologies: T Triassic Mudstones; S Sherwood Sandstone; M Permian ("Magnesian") Limestone; W Westphalian; Na Namurian; D Dinantian; CB Caledonian Basement; a indicates possible location of inter-block anhydrite deposits. Vertical exaggeration x 20.
Arrows indicate assumed groundwater flow paths

Figure 8: Conceptual model of the regional hydrogeology of the White Peak.

Acknowledgements

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The Sandstone Caves under Nottingham

Tony Waltham, Nottingham Trent University, tony@geophotos.co.uk

Figure 1. Cave entrances cut into the foot of Castle Rock, the type locality for the sandstone on which stands the city of Nottingham.

The city of Nottingham stands on an outcrop of Triassic sandstone that forms low hills on the north side of the River Trent. The broadest of these hills was the site of the original Saxon settlement, and the higher but smaller hill just to its west was occupied as the Norman stronghold in the year 1068 (Figure 1). The Norman town expanded until it merged across the Market Square with the Saxon town. The town area then occupied most of the sandstone outcrop immediately north of the low cliffs and bluffs that dropped to the Trent floodplain, and the town grew little more in size until the mid 1800s. The site of the old town is now roughly picked out by the inner ring road round the modern city centre.

Figure 2. SEM image of the Nottingham sandstone; well-packed sand grains mostly about 1mm across have little interstitial cement except for the tiny flakes of clay visible on some of the exposed surfaces.

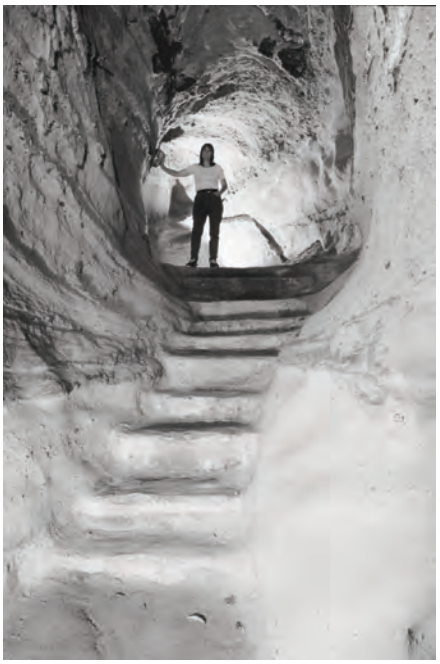

Figure 3. A cave inside Nottingham's Castle Rock, one of the few whose prime use was a passageway.

Nottingham's Triassic sandstone, locally known as the Nottingham Castle Formation within the Sherwood Sandstone Group, is distinguished by its low intact strength and its high rock mass strength. The sandstone has a high porosity, from which an initial calcite cement has been leached beneath all outcrops, so that only a weak clay cement remains (Figure 2). Its unconfined compressive strength (UCS) declines due to weathering near the surface; at the depths where nearly all Nottingham's caves have been created, at 2-5m below ground level, UCS is generally 5-10MPa. This material can be excavated with hand tools, with varying degrees of effort. The high rock mass strength of the sandstone derives from its minimal fracturing. Major bedding plane weaknesses, within a few degrees of horizontal, are restricted to scattered horizons of flood deposition rich in rounded pebbles and mud flakes.

This fortuitous combination of a weak material and minimal structural breaks makes Nottingham's sandstone an ideal tunnelling medium; it is easily excavated and yet stands safely over an unsupported span (Waltham & Swift 2004). This fact must have been appreciated by the early inhabitants of the region, who would have found it easy to create dwelling space by excavating into the foot of the sandstone cliffs along the edge of the Trent floodplain (Figure 3). Nottingham was documented as a "house of caves" by Asser, King Alfred's chronicler in the 9th century, but little more is known of these early cave houses. All have since been destroyed. Weathering causes cliff degradation and retreat, which has been matched by the townspeople cutting back the cliff

Figure 4. One of the more splendidly carved of Nottingham's caves, this was excavated in the 1740s as a wine cellar and perhaps a drinking den beneath the back garden of Lord Willoughby's town house.

profiles; new generations of caves were then excavated behind the position of those that had collapsed or been removed when they became unstable.

More than 500 caves are known under the city of Nottingham, but all of these are thought to date from post-1200, and only a small proportion are post-1850 (Owen & Walsby 1989; Waltham 1996). Practically all the available natural cliff faces had caves cut into them, some with multiple generations, but most of the caves were excavated underneath buildings, with stairway entrances and little or no natural light inside them (Figure 4). Most were effectively sub-basements under individual buildings, though some were dug out beneath the adjacent gardens or yards. Caves beneath buildings were generally dry, because the building itself prevented rainfall infiltration. Most caves are 2-6m wide and about 2m high, but could be as long as required or as dictated by the boundaries of the available land.

The main use for the caves was storage, especially for liquids, where the benefits of year-round constant temperature underground could be realised. Almost every inn and public house had its beer cellar carved out of the rock, with steps down from the bar and a vertical barrel-drop down from the backyard; many of these are still in use today. Caves were also used as work places. These include the medieval malt-kiln caves that are unique to Nottingham, of which thirty have been discovered to date (MacCormick 2001). Also distinctive are the three underground tanneries, with tanning pits cut into their rock floors (Waltham &

Figure 5. Part of the warren of galleries left in Rouse's sand mine

Figure 6. Weathering of sandstone in a cave that is open to the elements via a hillside doorway; grains of sand have fallen from the walls to pile up on the floor, leaving quartzite pebbles protruding from the retreating face.

MacCormick 1993); these have all been found in caves along the floodplain cliff, adjacent to the town's zone of 16th century tanneries that were mainly in the open and therefore of restricted use during freezing winters. Metal works, wagon works, monastic chapels, butchers, cisterns, ornamental follies, wine vaults and grocers' cold stores were among other uses for the caves, along with just a few access tunnels.

There were also three groups of mines, where sand was extracted (Waltham, 1994). The largest of these was worked by James Rouse and colleagues for about 20 years around 1800. This was a classic pillar-and-stall mine (Figure 5) with a random pattern created by selective hand-working to take the cleaner and perhaps the softer sandstone. Breaking it out from the working faces caused it to disintegrate into sand, which was carried out of the mine on donkeys through a gently inclined drift.

Only a handful of the caves are in use today. The remainder constitute a significant local geohazard with respect to urban redevelopment; larger buildings and heavier loads are now imposed upon ground that may be underlain by caves excavated and designed centuries ago to be covered only by smaller and lighter structures. The sandstone weathers by breakdown of its weak clay cement (Waltham & Cubby 1997). This is significant on exposed faces and also in caves open to circulating atmosphere (Figure 6), but is not a problem in caves that are virtually sealed behind doors or beneath houses.

Progressive redevelopment in the city has caused many caves to be lost, because their entrances have been changed, while their inner rooms remain open and potentially unstable. The hazard along roads is created when the sandstone is saturated by such as a leaking pipeline, so that it loses most of its modest strength and falls away from cave roofs in bedding units only about 10mm thick (Figure 7). Appropriate ground investigation is therefore needed prior to all new construction in the inner city, which is carefully controlled with respect to rock loading over the caves (Waltham & Swift 2004). Remedial works commonly involve concrete filling, but some caves have heritage values that mean they have to be protected while suitable foundations are placed around them or straddling them.

Figure 7. Cave roof failure where a leaking water main weakened the sandstone so that thin slabs could fall away; this cave lies under a road and has since been filled with concrete.

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Book reviews

Worlds on Fire : Volcanoes on the Earth, the Moon, Mars, Venus and Io, by Charles Frankel, 2005, Cambridge University Press, 358 pages, £25 (hardback) ISBN 0521803934.

This slim volume is designed for anyone interested in volcanic processes here on Earth and, as we see increasingly on our tv screens, on other planets and moons of the Solar System. It is written by an eminent geologist with vision.

The first chapter explains volcanology for the layman and revises the processes for students of earth sciences. The style is relaxed, with subsections listed in the Contents for easy reference ("Under the volcano" … "Volcanoes and climate"...). More detailed technical aspects are tucked into boxes ("Mid-ocean ridges" … "The great calderas" …).

The second chapter provides A tour of terrestrial volcanoes covering Krafla, Kilauea, Etna, Ol Doinyo Lengai (Tanzania) and Mount Pelée. Each has its own section starting with a photograph and basic data, followed by a description and some history; then Frankel suggests an itinerary around the volcano, taking in its special features (pseudocraters on Krafla) on the way.

Having used Earth to demonstrate his method and tour-guide format the author moves on to his main purpose – the exploration of volcanism on the Moon, Mars, Venus and Io. For each body he provides the detail of when it was visited by which spacecraft plus the technologies used to acquire the data and images. The text itself is a distillation of accurate and reliable information which, over the course of time, will be amplified by further investigations.

As for Earth, itineraries around five volcanic sites on each body make lively reading. The Moon's are illuminated by the spacewalks and recollections of the Apollo astronauts; the Martian sites by Russian and American missions and currently by Mars Global Surveyor (plus rovers) and Mars Express. The surprising surface of Venus was mapped by the early 1990s and is currently, since April 2006, being investigated by Venus Express. Five itineraries are included for Jupiter's moon Io, too, even though its volcanism was only revealed by Voyager 1 in 1979, followed by a visit from Galileo in 1997.

A bibliography, a selection of websites, an 8-page glossary and a thorough index are provided together with a section of 24 colour plates augmented by black-and-white pictures throughout the text. Altogether a helpful dependable summary of planetary exploration, focussing on twenty-five volcanic sites.

Sybil Richardson, BA (Hons) Open

The Geological History of the British Isles by Arlene Hunter and Glynda Easterbrook, 2004, The Alden Group, Oxford, 560pp, £18.50 (paperback) ISBN 074920138X.

Having just returned from helping at Summer School and having read the text several times, what can I say about this delightful book! It is written by our own tutors as part of the Open University Course SXR260 and many of you reading this will already be familiar with the text. It is aimed at undergraduate second level but is an ideal book for any student of geology or for the interested public. It has 123 pages of actual text plus a useful glossary and index. The book differs from the course text mainly through the incorporation of the bookmarks as plates into the centre of the book.

The book looks at the global view of Earth History and has a short chapter on plate tectonics. It then introduces the main lithotectonic units of the British Isles. Each of these is then explored in turn in the following chapters. The final chapter is on the Quaternary Period and each chapter finishes with a summary. Very useful for revising purposes!

I particularly like the way the book is set out in an easy learning style with short paragraphs interspersed with colour diagrams, maps and photographs that clearly illustrate the text. It explains the geological processes involved in forming Britain as we know it today but throughout it links this with the global position of the continents throughout Earth's history. This leaves us to consider the more holistic approach to geology that is explored in other courses.

The authors should be congratulated on providing not only a superb book in its own right but one that is accessible to anyone with an interest in geology.

Eileen Fraser BSc (Hons) (Open) DipEarthSci (Open) FGS

The Late Pleistocene and Holocene Evolution of the Trent Valley, UK

Andy J. Howard[1] and David Knight[2]

[1]Institute of Archaeology and Antiquity, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

[2]Trent & Peak Archaeological Unit, University Park, Nottingham, NG7 2RD, UK.

Abstract

This paper provides a brief summary of the landscape history of the Trent Valley, one of the major river corridors in England. Ameliorating climate in the immediate postglacial period led to the expansion of dense mixed deciduous woodland across the valley floor and the development of a meandering/anastomosing channel system. In the lower Trent Valley, both fluvial and vegetation development may have been influenced by sea level change. Around 4000 BC, the character of the valley floor landscape changed, demonstrated by the identification and dating of significant numbers of tree trunks inter-bedded within coarse sands and gravels. Whilst the causal mechanism of this change is not fully understood, tree trunks which were clearly felled have been identified in the lower Trent Valley. In the later prehistoric and historic periods, a variety of archaeological remains including fishweirs, anchor stones, bridges and mill dams point to increasing human activity on the valley floor and environmental evidence documents the increasing effects of agriculture on the catchment.

Introduction

The River Trent is the 5th longest water course in Britain and is the major arterial river draining the East Midlands. It rises on the Staffordshire Moorlands (altitude around 250m O.D.) and flows approximately 210km to the Humber Estuary (Ward 1981), draining an area of approximately 7,490km^2. Its key tributaries (Figure 1) dissect a diverse range of geological terrains including the Triassic sandstones of the Mansfield Plateau, the Carboniferous sandstones, shales and limestones of the Peak District, the Jurassic limestone uplands of the Leicestershire Wolds and the Precambrian and Cambrian igneous and metamorphic rocks of Charnwood Forest.

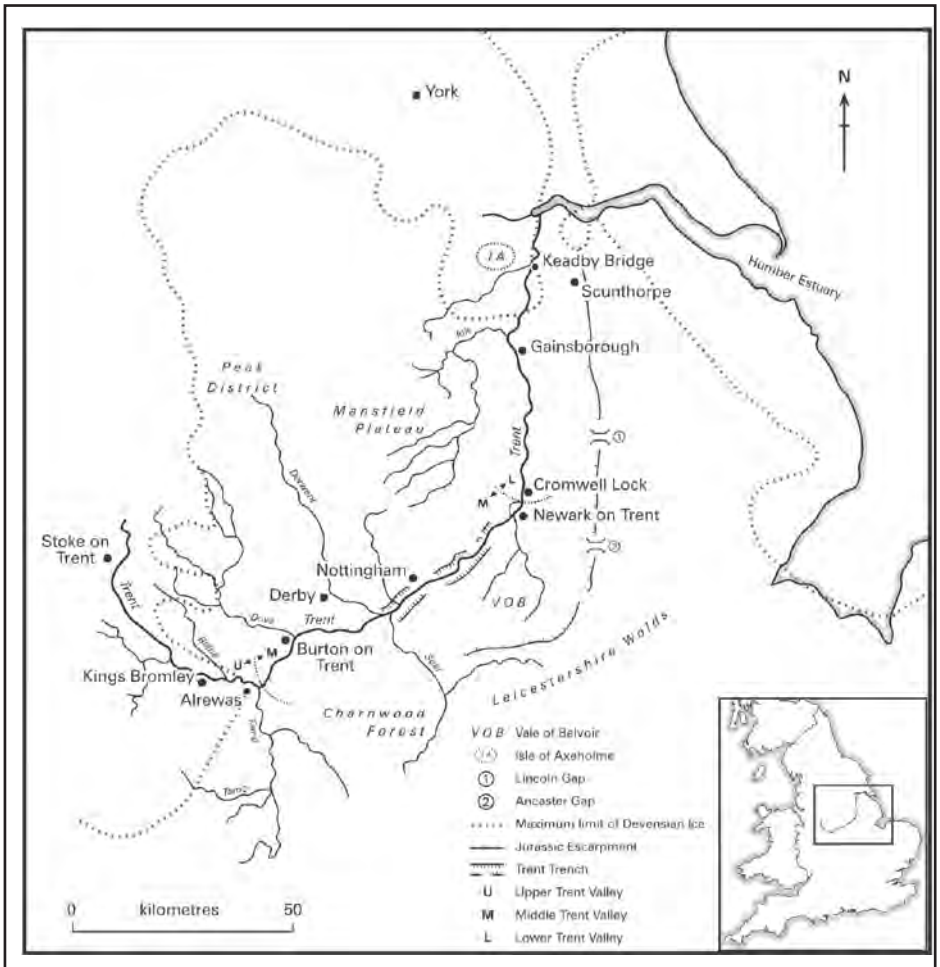

Figure 1. The River Trent, its tributaries and major physiographic features of the region referred to in the text. The maximum limit of Late Devensian glaciation is also shown. Reprinted with permission of John Wiley & Sons, Inc.

The valley corridor of the Trent and associated ancestral rivers such as the 'Bytham', of which the Trent may once have formed a part (Rose 1994), have undoubtedly been important corridors for human movement since Lower Palaeolithic times, as demonstrated by the range of artefacts recovered (Posnansky 1963; Graf 2002; Keen *et al.* 2006). Through the Holocene, this occupation intensified and the Trent Valley contains a diverse range of evidence for human activity recorded from cropmarks (Whimster 1989), through the excavation of settlements (Knight 1991; Riley *et al.* 1995; Loscoe-Bradley & Kinsley 2002) and less well understood monuments such as burnt mounds (Beamish & Ripper 2000) as well as artefactual material (Allen *et al.* 1987). Much of this archaeology is recorded on gravel terraces of Pleistocene date, which historically were the major focus of gravel extraction. Today, the Trent Valley is one of the major aggregate-producing regions in the UK. Quarrying has continued on the Pleistocene terraces, but has also expanded onto the Holocene floodplain, leading to the discovery of further archaeology. Such remains include medieval bridges (Cooper *et al.* 1994) and mill dams (Clay & Salisbury 1990), prehistoric log boats (MacCormick *et al.* 1968) and metalwork (Scurfield 1997) and fishweirs of various dates (Salisbury 1991, 1992). In addition, quarrying has exposed organic-rich sediments from a range of floodplain environments, which have been

dated and analyzed for their pollen, insect and plant macrofossil assemblages (Ellis & Brown 1998; Howard *et al.* 1999a, 1999b).

Since the implementation of Planning Policy Guidance note 16 in 1990 (Department of Environment 1990), elucidating natural and cultural landscape development through geoarchaeological research undertaken and funded as part of development control has become a key research theme of regional archaeological curators. This paper briefly summarizes the results of this work to date.

Late Pleistocene Inheritance

By *c.* 13000 years BP, climatic amelioration had resulted in the wastage of the Dimlington Stadial ice sheet covering much of northern Britain (Lowe & Walker 1997). In the Lower Trent Valley and Vale of York, the blockage of the Humber Estuary by ice (Figure 2) led to the impediment of regional drainage and the development of proglacial Lake Humber. In the Vale of York, radiocarbon dating indicates that Lake Humber had probably silted up by 11 100 ± 200 BP (Gaunt *et al.* 1971; N-810). An insect fauna from Sandtoft (Figure 2) in sediments immediately succeeding the lacustrine sediments indicates conditions at least as warm as the present day (P C Buckland pers. comm.). The improvement of climate was accompanied by increasing hunter-gatherer exploitation of the regional landscape (Garton 1993), although it is likely that humans were probably periodically present regionally from Oxygen Isotope Stage 3, around 50,000 years ago (Jacobi *et al.* 1998).

Palaeoenvironmental records from the Trent Valley during this Late glacial time-frame are rare. A clast of organic material from near the base of the sand and gravel sequence at Hemington Quarry (Figure 2), dated to 13180 ± 250 BP (Beta 93855; 14740-12470 *cal.* BC), provides the only palaeobiological record (Greenwood & Smith 2005), but the accuracy of this radiocarbon date is questionable due to potential 'hardwater effects' (M Greenwood pers. comm.). Nevertheless, Coleopteran remains recovered include species that today are restricted to sub-arctic environments and those now limited to montane areas. The insect assemblage suggests that the deposit probably accumulated in a still, stagnant, pool of water, which was surrounded by dwarf willow and sedges. Palaeotemperature reconstructions from the insect remains suggest that the mean annual temperature was between –6˚ and –10˚ C, with July temperatures as low as 10˚C and winter temperatures as low as –20˚C (Greenwood & Smith 2005). At Tiln in the Idle Valley (Figure 2), an organic deposit infilling a scour hollow in basal sands and gravels and dated to 11250 ± 80 BP (Beta-100931; 11760-11280 *cal.* BC) provides a similar environmental picture (Howard *et al.* 1999b).

The Loch Lomond Stadial (11 000-10 000 years BP) was marked by a return of cold periglacial conditions to the region. With limited vegetation cover, fine grained fluvial and glacial sediments on valley floor and terrace surfaces were redistributed by aeolian activity to form extensive blankets of coversand (Bateman 1995).

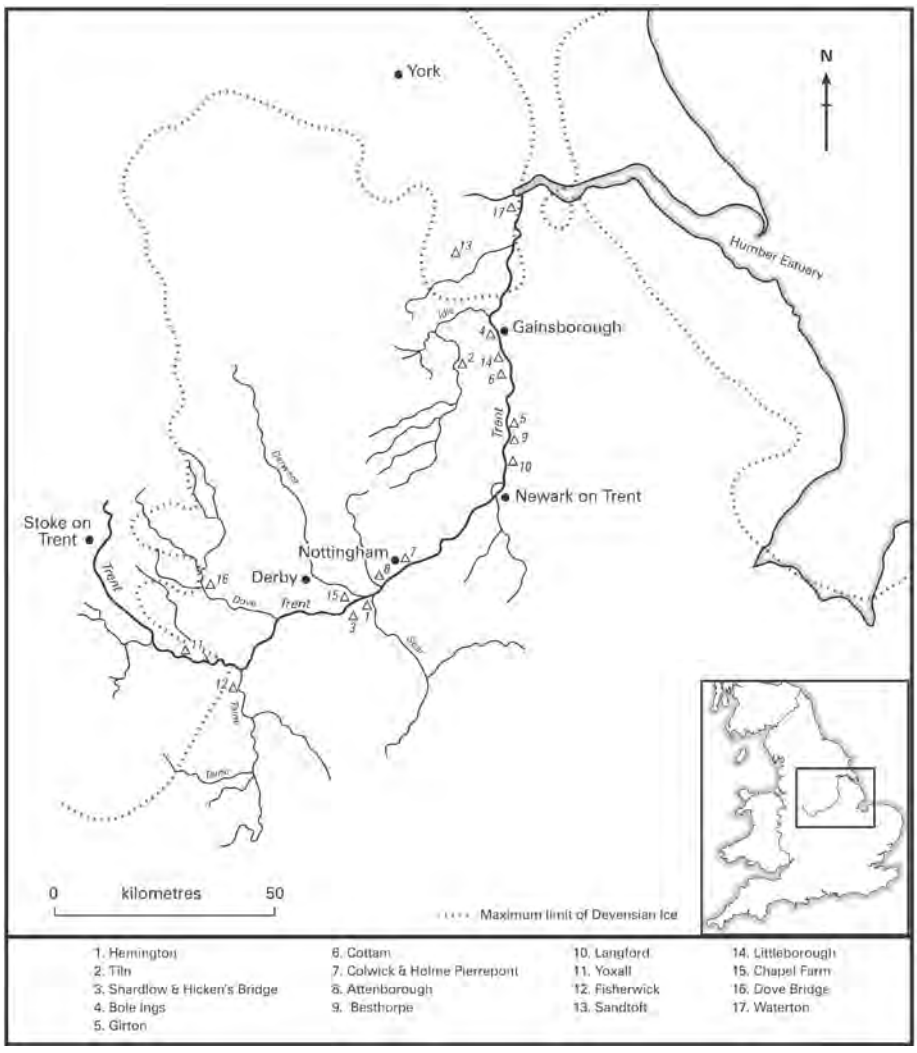

Figure 2. The River Trent, its tributaries and localities referred to in the text. Reprinted with permission of John Wiley & Sons, Inc.

Holocene landscape development before 2000 cal. BC

Renewed climatic amelioration during the early post-glacial was accompanied by vegetation colonization and the development of mixed 'wildwoods' (Rackham 1996). Incision in the lower Trent and adjacent perimarine lowlands of the Humber Estuary (Figure 1) was associated with sea-levels that were approximately 17m below present by 8000 years cal. BP. This phase of incision was replaced by rapid sea-level rise during the remainder of the early Holocene, with marine transgression peaking by 3000 years cal. BP. However, the intercalation of freshwater peats, alluvium, archaeological remains and marine deposits well into the mid-1st millennium AD indicates the delicate balance of terrestrial and marine processes (Metcalfe *et al.* 2000).

In lowland river valleys across Britain, several studies indicate that the combination of low channel gradients and the predominance of fine-grained sediment and vegetated channel banks resulted in the development of stable, multi-channelled (anastomosed) river systems from the early Holocene (Rose *et al.* 1980; Brown *et al.* 1994). In the Trent Valley, pollen and insect

remains from a palaeochannel fill at Bole Ings near Gainsborough (Dinnin 1997; Brayshay & Dinnin 1999) indicate that by at least 7500 *cal.* BC, if not earlier, large channels had started to be abandoned and had become infilled with organic-rich sediment. Analysis of approximately 8m of organic-rich sediment from one borehole at Bole Ings has provided the longest and most complete record of palaeoenvironments for the Trent Valley, spanning a period of ca. 6500 years between *ca.* 7300-800 cal. BC. These data illustrate that, between 7300 and 5200 *cal.* BC, the landscape was characterized by a wooded floodplain comprising willow and poplar along the riverbank/wetland margins, with Scots Pine on sandier levees and deciduous hardwoods of oak, lime and elm at some distance from the floodplain. The low frequencies recorded of plants associated with disturbed ground and grassland suggest that open habitats were minor components of the vegetation mosaic.

Around 5200 cal. BC, alder carr woodland developed on the floodplain at Bole Ings (Dinnin 1997; Brayshay & Dinnin 1999), possibly in response to continuing changes in catchment hydrology associated with sea-level change and rising groundwater tables leading to waterlogging. In the understorey of the fen carr, ground cover included ferns and woody climbing plants. A deterioration in the preservation quality and composition of pollen and insect assemblages between *c.* 4000-1960 cal. BC suggests some change in floodplain hydrology, possibly in response to down-draw of the water table associated with the deeper penetration of alder roots into floodplain soils. Some decline of elm, pine, lime and hazel also implies a wider change in the landscape vegetation, while the increasing presence of particulate charcoal may suggest deforestation on the drier parts of the floodplain as a result of human activity. However, in general, the palynological and entomological evidence supports the concept of continued floodplain stability, with sedimentological evidence from intercalated peats and silts suggesting deposition of sediments in a series of riparian wetlands and low-energy anastomosing channels.

At Cottam, less than 10km south of Bole Ings, an organic floodplain sequence dated on the basis of its pollen assemblage to around 3700 cal. BC provides a similar picture of alder carr and mixed deciduous woodland (Scaife & Allen 1999). However, the presence of cereal type pollen and disturbed and bare ground taxa in the upper part of the sequence indicates localized agricultural activity.

Whilst the palaeoenvironmental datasets from Bole Ings and Cottam provide a relatively detailed reconstruction of early post-glacial environments in the lower Trent Valley, no long sequences of peats have been analyzed upstream of Newark, where the effects of sea-level change would probably have been limited. The only palaeoenvironmental record currently available from this area is a snapshot provided from the analysis of a single sample of pollen from a small, peat infilled palaeochannel at Hicken's Bridge, Aston upon Trent (Figure 2), dated to 7730 ± 80 BP (Beta 90519; 6650-6400 cal. BC). This assemblage suggests that hazel was dominant, growing adjacent to the channel, although willow may have grown in damper areas, interspersed by small open areas of fen-like grassland. Elm, pine and occasional grains of oak, alder and birch indicate that other species were growing, presumably on higher, drier parts of the floodplain (Howard unpublished).

Other palaeoenvironmental information upstream of Newark is provided by dendrochronologically and radiocarbon-dated oak tree trunks stratified within the sands and gravels. These trunks, many with intact root boles, were first noted by Salisbury *et al.* (1984) in the gravel quarries around Colwick and Holme Pierrepont near Nottingham (Figure 2). One group of 27 trunks was dated to between *ca.* 4200-3900 BC and another group of 11 trunks were ascribed to the period from *ca.* 2000-1600 BC; a number of other trunks spanned a range of timescales. Plotting of the positions and orientations of these dated trunks (and associated archaeological evidence) allowed Salisbury *et al.* (1984) to reconstruct a detailed pattern of local river channel change. This approach was repeated with great success elsewhere in the Trent Valley by Salisbury (1992) and demonstrates how detailed recording can provide valuable geoarchaeological information even where extensive reworking of the alluvial and archaeological sequence has occurred. Careful examination of the trunks at Colwick and Holme Pierrepont provided no evidence for their felling by humans or by animals such as beaver (see Coles 1992). However, at Langford Quarry, approximately 8km downstream of Newark (Figure 2), tree remains within a channel log-jam dating to the period *c.* 2300-2000 BC showed clear evidence of felling (Howard *et al.* 1999a).

The size of the tree remains recorded throughout the valley suggests that they were part of dense floodplain woodland and has been corroborated by both the palynological and entomological evidence. The preservation of intact root boles on many of these trees suggests that they were thrown into the river by the undercutting of channel banks during periods of enhanced fluvial activity. However, whether this changing catchment hydrology was driven by climate (changing flood frequency and magnitude) or by land use change remains debatable. For example, evidence from Bole Ings supports the concept of considerable floodplain change marked by a reduction in woodland and scrub taxa, a corresponding increase in grassland and reedswamp, and a change from woody silty peat to organic silty clay deposition (Brayshay & Dinnin 1999). However, there is no corresponding rise in beetle faunas indicative of grassland, disturbed or open ground taxa. This latter observation led Brayshay & Dinnin (1999) to conclude that the sedimentological and palaeoecological changes recorded at Bole Ings were a function of changing environmental conditions associated with increased wetness arising perhaps from sea-level change in the Humber Estuary (Long *et al.* 1998) rather than the expansion of grassland or agricultural activity.

In the lower Trent, in addition to the extended record from Bole Ings, at least three other organic-rich channels have been identified on the floodplain immediately north of Girton (Howard *et al.* 1999c). Radiocarbon dating indicates that at least two channels were in use and infilling with organic sediments from the Middle Bronze Age into the Iron Age/Romano-British period. Preliminary environmental assessment from pollen, macroscopic plant and Coleopteran remains indicates a slow-flowing, shallow, swampy water body, approximately 1.5m deep, surrounded by reedbeds and alder-willow fen woodlands. This anastomosing riparian wetland zone was surrounded by a valley floor cleared and farmed with a mixed arable and pastoral economy, although patches of mixed oak, birch and hazel forest existed some distance away (Howard *et al.* 1999c). Farther upstream at Yoxall (Figure 2), pollen, plant macrofossils and Coleoptera remains

from a palaeochannel of the Trent dated to 2780 ± 60 BP (Beta 73350; 1049-810 *cal.* BC) indicate a slow-flowing or still, nutrient-rich water body, occasionally recharged by flooding (Smith *et al.* 2001). The banksides were muddy and densely vegetated with sedges, rushes and alder woodland. Away from the channel, mixed forests of oak, hazel, lime, birch and ash were a significant component of the valley floor landscape. There is some evidence of woodland clearance and cultivation in the upper parts of the sequence, which also coincides with a change in sedimentation from peat to clay. As well as plants indicative of disturbed and bare ground, cereal pollen and insect remains indicative of grassland, there is limited circumstantial evidence for the development of dry, acidic heathland, possibly indicating land mismanagement.

Holocene landscape development after 2000 *cal.* BC

In contrast to the time period 2000-600 BC, geoarchaeological evidence for valley floor evolution between 600 BC and AD 1000 is relatively rare. The most detailed geoarchaeological record available for the region for the later prehistoric (Iron Age) period is from the palaeobiological analysis of ditch fills at the settlement of Fisherwick (Figure 2) in the tributary valley of the River Tame in the Upper Trent (Smith 1979). Pollen and Coleoptera indicate that by *ca.* 100 BC the river terraces of the valley floor had been all but cleared of woodland and that a mixed arable and pastoral farming economy was being practiced (Greig *et al.* 1979). Despite the absence of forest on the terraces, alder accounted for 58% of waterlogged wood and 41% of arboreal pollen recorded, which suggests that the riparian zone was still wooded. In this type of economy, the contemporary floodplain would have provided rich summer grazing, hay for winter fodder, and raw materials (such as willow) for making wattles, hurdles and basketry (Greig *et al.* 1979). Fisherwick is less than 10km from Yoxall (Smith *et al.* 2001), which suggests that within *ca.* 1000 years human activity had changed this part of the Trent Valley landscape from dense woodland to arable fields and grassland.

Only four other palaeochannels have been identified for this time period and analyzed as part of preliminary geoarchaeological assessments. Three of these palaeochannels are from the floodplain of the lower Trent north of Girton (Howard *et al.* 1999c) and provide radiometrically dated evidence of fluvial activity during the Iron Age and Romano-British periods, from *ca.* 400 *cal.* BC to *cal.* AD 200. The dates indicate that at least two channels were in use simultaneously and were infilling with organic sediments. Preliminary environmental assessments from pollen, macroscopic plant and insect remains indicate slow-flowing, shallow, swampy waters, approximately 1.5m deep, analogous to an anastomosed wetland channel system; these were surrounded by reedbeds and alder-willow fen woodlands, with patches of mixed oak, birch and hazel forest farther away. With the exception of the riparian zone, the floodplain was largely cleared and farmed as part of a mixed arable and pastoral economy (Howard *et al.* 1999c).

Other evidence of valley floor environments is provided by the analysis of sediments associated with three Iron Age/Romano-British dug-out canoes discovered at Holme Pierrepont near Nottingham (Figure 2) (MacCormick *et al.* 1968; Cummins & Rundle 1969). The canoes were buried within point bar sands and gravels deposited by a channel estimated to be 3m deep and 60m wide. Molluscs recovered from near the base of the sands and gravels indicate a large, clear, relatively slow moving body of hard water, with a muddy substrate supporting weed growth. The relatively rapid burial of these canoes in the deepest part of the channel (Cummins & Rundle 1969) almost certainly suggests their loss during flood events. A similar scenario can be envisaged for the recently discovered remains of a Bronze Age dug-out canoe from Shardlow Quarry that was dated to 3115 ± 24 BP (OxA 9536, OxA 9537; 1440-1310 *cal.* BC; C Salisbury pers. comm.; Garton *et al.* 2001).

From the early historic period, there is evidence from the lower Trent Valley of a change in the style and rate of valley floor alluviation, from organic-rich silts and clays to inorganic red brown silty clays. This change was initially noted at a number of archaeological sites in the region, including Sandtoft on the banks of the River Idle (Samuels & Buckland 1978) and Littleborough (Figure 2) (Riley *et al.* 1995), adjacent to the Trent. In both cases, the inorganic silty clays are buried or interleaved with Romano-British archaeology. Buckland & Sadler (1985) have argued that this alluviation was caused by catchment soil erosion brought about by changing agricultural practices introduced by the Romans, such as the introduction of new ploughs capable of severing the root mat and the growing of winter cereals. This change in sedimentation style is now recorded throughout the region, with recent research suggesting that it may have started in the later prehistoric period (Knight & Howard 2004).

The dendrochronological and radiometric dating of a timber bridge removed from the river bed at Cromwell Lock (Figure 1) near Newark to *c.* AD 500 provides probably the earliest evidence of engineering within the channel zone (Salisbury 1995). From *c.* AD 600, further evidence of human interference for management and fishing is recorded by the discovery of a number of post-alignments and more intact fishweir structures in sands and gravels at Colwick and Hemington in the middle Trent (Salisbury *et al.* 1984; Salisbury 1992).

From AD 1000-1900, evidence for the development of the valley floor is provided by geoarchaeological data from quarries at Colwick, Holme Pierrepont and Hemington (Figure 2). The spatial recording of fishweirs, anchor stones, post alignments, revetments, a mill-dam and three medieval bridges (Salisbury *et al.* 1984; Clay & Salisbury 1990; Cooper *et al.* 1994; Salisbury 1992) provides evidence not only of the significance of human activity but also of considerable channel change and mobility in this part of the valley floor. Other studies of floodplain stability along the middle Trent during the past 400 years found that 79% of the valley floor had experienced instability, usually within a 200m corridor of the contemporary channel (Large & Petts 1996). In the Hemington reach, Brown (1998) has demonstrated that between the 9th and 15th/16th centuries, reworking of the valley floor has been associated with channel change from a single meandering river, through multi-channeled braided and anastomosed systems, before returning to a single channel. A similar pattern of floodplain instability has been recognized in the vicinity of Colwick, but appears to have occurred *ca.* 100-200 years later (Brown *et al.* 2001). Increased flood frequency and magnitude associated with climatic variability, particularly during the Medieval Warm Period (*ca.* AD 900-1300), is the mechanism used to explain this floodplain metamorphosis. The delayed downstream response between Hemington and Colwick is argued to reflect the time-lag associated with the movement of the 'sediment slug' through the valley (Brown 1998).

Conclusions

This paper provides a review of the Holocene evolution of the Trent Valley based on geoarchaeological research. Continued data collection will help refine our current models of landscape development and allow key research questions to be addressed. The majority of geoarchaeological studies undertaken in the Trent Valley and elsewhere in the UK have only been made possible by developer funding since 1990, principally by aggregate companies and the continued exploitation of mineral resources will no doubt spur further significant developments in our understanding of the region's environmental history.

Acknowledgements

Many of the research themes developed in this paper are based upon fieldwork funded by the commercial sector as part of PPG16. Additional research has been undertaken as part of the Trent Valley Survey, funded by Nottinghamshire County Council, Derbyshire County Council and English Heritage and since 2002, by funding from the Aggregates Levy Sustainability Fund (via English Heritage). Thanks are also extended to the members of the Trent Valley Geoarchaeology (www.tvg.org.uk), which provides a focus and forum for discussing geoarchaeological research in the Trent Valley and wider East Midlands region.

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Book review

Hydrology. An Introduction by Wilfried Brutsaert, 2005, Cambridge University Press, 605pp (hardback) £40, ISBN 139780521824798

This is an excellent textbook, which is based on the course that the author has taught at Cornell University for the past 30 years. It covers the fundamental principles of hydrology and is aimed at final year undergraduates and postgraduate students in engineering and physical sciences. Following an introduction, which defines the hydrological cycle and other basic concepts, the book is divided into four parts. Part 1 deals with water in the atmosphere and the key issues of precipitation and evaporation. Part 2 considers water on the surface of the ground and Part 3 water below that surface. In Part 4 the various strands are brought together to look at flow on a catchment scale, in response to precipitation. The physics and mathematics necessary to describe the various phenomena are introduced and developed and readers will require a sound knowledge of calculus and fluid mechanics. Throughout, the main subject matter is represented in regular type and more advanced material in smaller type with a grey rule in the left hand margin. Thus readers can readily avoid more advanced material if they wish.

For geology students Part 3, consisting of three chapters, is particularly relevant. The first chapter looks at flow in porous media and includes a discussion of the original experiments carried out by Henry Darcy, described in a report of 1856 on the water supply of Dijon, the capital city of Burgundy. Darcy's Law will be known to all students of petroleum geology and hydrogeology and celebrates its 150th anniversary this year. The second chapter deals with the infiltration of water into the soil and its subsequent vertical movement through the soil and unsaturated zone and chapter three with groundwater discharge. Readers need to remember that the author is looking at groundwater from a surface water perspective and thus there is nothing on groundwater abstraction and many other aspects of interest to environmental geologists.

For me the highlight of the book is the final chapter, just over 30 pages in length, which provides an historical sketch of theories of water circulation on the Earth and the origin of springs. Here we read about the seawater infiltration and rainfall percolation theories of the ancient Greeks; the concept of Aristotle that water was formed out of vaporous air beneath the Earth's surface and Edmund Halley's experiences on St Helena where the night time condensation was so heavy that he thought such water must be the origin of springs. This book is worth having for the final chapter alone but also provides an authoritative introduction to hydrology, both as a textbook for advanced students and an invaluable resource for professional engineers and Earth scientists.

John Mather (Family member of OUGS)

Landscapes Natural and Manmade

Malcolm Barton, Regional Director, Groundwork Yorkshire and the Humber

Examining the drivers of land use

Regeneration efforts by successive governments over the past three decades have mainly concentrated on trying to overturn the socio-economic problems left behind by the demise of the industrial age that spanned the previous two centuries. Driven by political necessity, efforts have been concentrated on trying to re-build the employment and wealth of communities that were left behind by the closure of the traditional heavy industries of coal mining, iron and steel production, chemical production and so on.

Regeneration activity during this period appears to be based on the premise that employment must be rebuilt and located where communities also exist. The presence of a population has in other words become the driver for land use and landscapes. This has not always been so; in fact most of the development of man and man's endeavours within the landscape have been driven by an entirely different set of conditions. We can explore this further by asking why, say, Sheffield, with a current population of some half million people, exists where it does, at that particular size, at this particular time. The answer is that Sheffield became established and grew as a result of the geology that exists in that part of the Don Valley located in South Yorkshire.

The technological revolution that brought about the growth of Sheffield commenced, according to some commentators, in a small town in Shropshire in the latter half of the 18th Century when the Quaker iron masters of Ironbridge developed methods for smelting iron by the use of coal and limestone. Both these naturally occurring resources together with ironstone were to be found together in that locality near the River Severn. It was the combination of these resources that sparked off the socio-economic revolution that only came to an end at the closing of the second millennium. Sheffield exists where it does because of the coal in the South Yorkshire coalfields, a local abundance of ironstone, and limestone located but a few miles away in the Peak District. In short, the population of Sheffield grew as a result of these geological resources.

Until the termination of the industrial revolution, man's relationship with landscape has always been connected to the resources found on or under the land. Whether we consider hunter-gatherers, early farmers or the fathers of the industrial revolution, geology as a shaper of land and provider of resources has always been one of the primary drivers for man's location within landscape.

Figure 1. An elderly man and a young girl born into completely different working conditions.

The elderly gentleman in Figure 1 in all probability left school before the age of 15 and worked, if not for the same employer, most probably in the same industry for most of his working life. He would have lived near to his employment and raised his family in that location. He was inexorably linked to place through his employment, just as his employment was inextricably linked to the place through the geological resources. The little girl in the same photograph has been born into a world that is markedly different. She lives in a world driven by global economics, where a call centre located in India might well deal with a query relating to an Internet account in the United Kingdom. She will live her life from now on against a backdrop of exponential economic and social change. It may well be that when observers look back at the short span of years of the latter half of the 20th Century they will realise that in the few years of the closing quarter of the last century of the last millennium, man's symbiotic relationship with place changed radically.

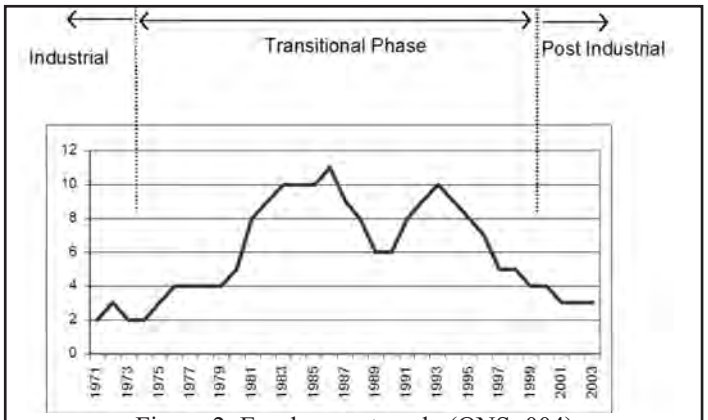

Figure 2. Employment cycle (ONS, 004).

The legacy of post-industrial land

The graph in Figure 2 shows the socio-economic effects that have characterised the shift from industrial to post-industrial society through a transitional phase that occupied but a brief 25 years. The graph charts the movement in claimant count during the period from 1975 to 2004 by which date the level of employment was approximately the same as it was at the end of the industrial period. The policies of successive governments that led to the huge effort to regenerate our industrial communities, was based on the requirement to re-build new forms of wealth following the end of the traditional industrial means of wealth creation. Figure 3 demonstrates that Gross Domestic Product (GDP) climbed at a steady rate throughout the entire phase. Whilst there appears to be an interesting paradox in that there is no statistical correlation between unemployment (measured by claimant count) and the growth of GDP, it can nevertheless be asserted that the drive to regenerate society through continued wealth generation and a return to high levels of employment was highly successful. However there were consequences of some significance in the

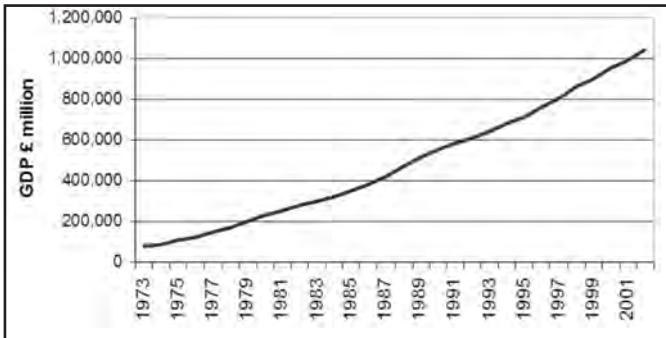

Figure 3. GDP £million at current prices.

relationship between man and landscapes. One of these was the legacy of a large stock of post-industrial land – often referred to as brownfield land.

Through the National Land-Use Database (NLUD) the government has tracked the quantity of brownfield land from 1998 to 2004. The results can be seen in Figure 4. The NLUD database shows that the stock of brownfield land has remained static at around a level of 60,000ha throughout the entire period. This is a relatively short timescale for the dataset but it is possible to get a better overall picture by looking at the surveys of derelict land undertaken between 1973 and 1993. These are shown in Figure 5 and reveal that the stock of derelict land remained similarly constant throughout that entire period at a level of around 40,000ha. The two datasets, while not being the same, do overlap and the striking feature is that notwithstanding the huge amount of investment by successive governments throughout the entire period, the stock of post-industrial land remained remarkably obdurate to change. Figure 6 gives some clues as to why this might be. In simple terms, the stock of derelict land remained constant because the rate at which new dereliction occurs is only marginally exceeded by the amount of land reclaimed and restored. A survey by English Partnerships a few years ago confirmed that a significant proportion of this land sits under the heading of hardcore dereliction.

It is not difficult to understand the reason why the transformation to a post-industrial society has left a substantial legacy of damaged land. The traditional industries of the industrial age were large consumers of both labour and land whereas the commercial industries and activities of the post-industrial era require fewer people and a smaller spatial footprint in order to generate the same or increased amounts of GDP. The inevitable result is a significant stock of surplus post-industrial land.

Because of the symbiosis between land and people in the industrial era it is inevitable that post industrial damaged land now blights those communities that developed at those same locations.

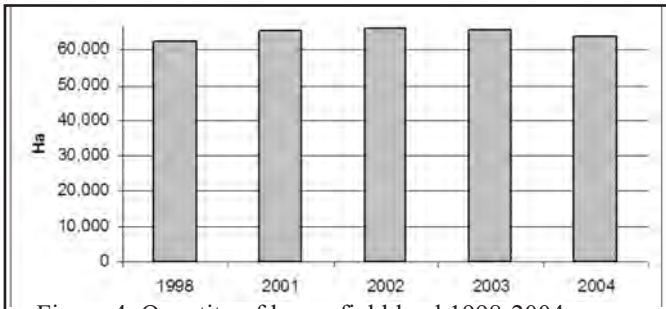

Figure 4. Quantity of brownfield land 1998-2004.

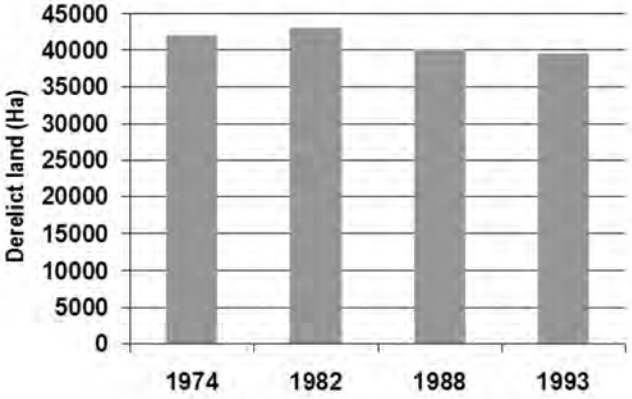

Figure 5. Stock of derelict land 1974-1993.

Plotting the index of multiple deprivation in the United Kingdom reveals that the highest rates inevitably coincide with those post-industrial areas that have suffered the most stress and change. Damaged land is not only a visual blight to these communities, it can be the source of contamination that slowly poisons the environment, it can be a focus for unsociable activities, it can be a magnet that draws children to play and it can lower a community's sense of self-esteem. Doing nothing about post-industrial dereliction should not be an option.

Turning blight into opportunity

Although post-industrial land can indeed be viewed from one perspective as blight, it is nevertheless the case that the stressed soils and landscapes of previously used land are often potent drivers for high rates of bio-diversity. Even as the transitional phase was getting underway in the early 70s conservationists were starting to observe the ways in which abandoned sites were naturally re-vegetating and also being informally appropriated by communities for informal recreational activities. An early seminal work was written by William (Bunny) Teagle who, with support from the Nature Conservancy Council, wrote *The Endless Village* (NCC, 1978), an observation of the naturally regenerating landscapes of the Black Country in the West Midlands. Such work has continued in virtually unbroken sequence through to the present day.

The work of Professor Tony Bradshaw reporting on the ecology and reclamation of derelict and degraded land provided a firm foundation for successive ecologists and environmentalists to increasingly understand and celebrate the fact that a paucity of fertility and nutrients could lead to more interesting landscapes. The same phenomena were observed by Oliver Gilbert in

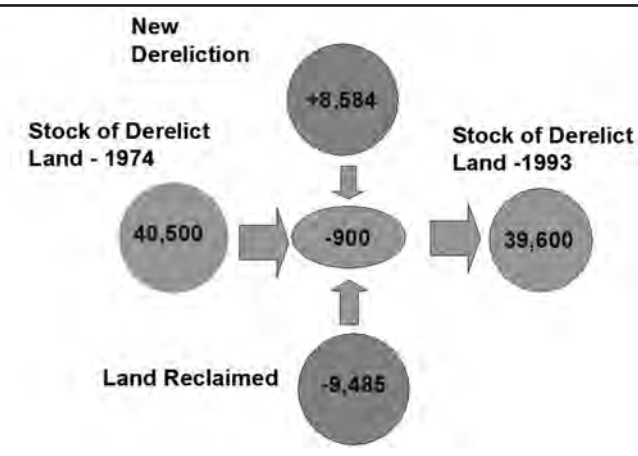

Figure 6. Flow diagram of derelict land reclamation.

Sheffield on slum clearance sites that had naturally re-vegetated, leading to his development of the idea of what he termed 'urban commons'. More recently Professor John Handley of Manchester University and Professor John Rodwell of Lancaster University have joined in various projects with environmentalists at Groundwork UK to extend the ideas and to demonstrate that ecologically informed, community led approaches to land reclamation can turn post-industrial blighted landscapes into potent socio-environmental assets.

Building on, and extending the broad foundation of academic work, Groundwork and other environmental bodies such as the Urban Wildlife Network, the British Trust for Conservation Volunteers (BTCV), the Wildlife Trusts, the Royal Society for the Protection of Birds (RSBP) and many other environmental organisations have demonstrated that post-industrial land can deliver benefits in terms of improved biodiversity, health, leisure and recreation, flood reduction and so on. This notion of multi-functionality has now started to find a new expression in the concept of Green Infrastructure.

Because of its origins and its correlation with communities, post-industrial land forms an important component in the mosaic of green spaces that aggregate to form Green Infrastructure. These landscapes can be used as a stage or a backdrop on which and against which many social and economic activities can take place. In such a way the developed landscape and ecology of a previous colliery site can now, for example, be used as an environmental setting within which to run projects that help disaffected teenagers to re-engage with society, helping them to be eased back into full time education. Land that was once used because of its inherent resources – coal or limestone or salt – can now find a new use helping to heal communities by helping to make them more healthy. Post –industrial landscapes can also be a vehicle for passing on to future generations a more bio-diverse environment. As Figure 7 shows, communities need not sever their original industrial and cultural links with these places but can use the new spaces to celebrate the industrial past. The photograph is an aerial view of one of the largest earth sculptures in Europe on the reclaimed Penallta Colliery site in South Wales. The sculpture is of Sultan, the last pit pony to work down the mine. The work now forms a critical component of the Penallta Community Park and was conceived by an artist working to a commission with the community to design a feature that linked the present and the past. A naming competition amongst local school children formed part of an educational project that allowed them to understand their local heritage even though they had never themselves witnessed a working mine. Penallta Community Park site and many similar examples provide potent proof of how the careful restoration and stewardship of the land can add substantial value to our environmental assets, improve the socio-economic and physical well-being of citizens and help to deliver sustainable communities.

Figure 7. A sculpture of the last pit pony Sultan, Penallta Colliery, South Wales.

Book review

Fundamentals of Structural Geology by David D Pollard Sand Raymond C Fletcher 2005, Cambridge University Press, 512pp, £45.00 (hardback) ISBN-139780521839273.

Pollard and Fletcher state in their preface that they have produced a text book which "emphasizes modern techniques of field data acquisition and analysis, the principles of continuum mechanics and the mathematical computational skills necessary to describe, model and explain quantitatively the deformation of rock in the Earth's lithosphere." As such it is designed for final year undergraduates and graduates who have taken courses in mathematics and physics in addition to physical geology. It is not a book to be read in isolation, as supporting material is available on an associated homepage available on the World Wide Web.

The authors explain to us the wide variety of problems associated with structural geology and use this to demonstrate the opportunities available to the student. A description of structural mapping techniques and tools follows before the full introduction of the mathematical and mechanical techniques. The mathematics relies heavily on differential calculus, vector analysis and matrix theory. A welcome revision of physical quantities, fields, dimensions and scaling is provided with specific reference to earth science processes. Each chapter takes the reader through the various topics associated with rock deformation from stress and strain to rheological behaviour and provides the mathematical tools to develop a better understanding of the processes at work and to develop an investigative methodology. A final chapter concentrates on model development and summarizes the concepts used in the book in the production.

The authors have taken the opportunity to educate using multimedia, and the website provides a comprehensive addition to the material in the book, including full colour images of the photographs in the text. The website, which is still under construction, provides supplementary material and allows for expansion with appendices which are yet to be developed to provide text additional to the book. The website is easy to navigate and use and provides further links to useful sources of information. This package provides an ideal method to gain a better understanding of the mechanics of structural geology

Mike Hermolle, BSc (Hons) NatSci (Open)

Potential effects of flank collapse of the Cumbre Vieja volcano, La Palma, Canary Islands

Tracy Chamberlain

Abstract

In 2001 scientists announced that a volcano on La Palma, Canary Islands was in the early stages of instability and that a future eruption may cause as much as 500km^3 of volcano to plummet into the surrounding Atlantic Ocean causing a mega tsunami. Such an event has not occurred in historic times. The Cumbre Vieja is the youngest in a series of La Palma volcanoes. Two previous volcanic episodes ended in large flank collapse. An eruption of the Cumbre Vieja in 1949 followed a period of over two hundred years of dormancy and created a series of faults between two eruptive vents. These faults are believed to be a surface expression of a much deeper fault. A small network of EDM (electronic distance measurements) was used during the 1990s to establish whether any a-seismic creep on the western flank had occurred. During periods of quiescence the faults appear to be stable and do not pose any immediate threat of collapse. However intrusion of fresh magma, increasing pore pressure and seismic activity are likely to be triggers for a future collapse.

Evidence of large flank collapse causing mega tsunamis in the Atlantic is scarce and uncertain. Mega boulders and chevron ridges that exist in the Bahamas and deposits on Lanzarote were created by large waves which may have been tsunamogenic. Using data modelling techniques tried out on smaller volcanic edifice collapses, computer models have been created to estimate wave propagation, speed and height following collapse. Plans and actions to mitigate the effects of volcanic collapse are surprisingly few. There are two seismometers on the volcano and National Oceanic and Atmospheric Association has announced plans for an Atlantic tsunami warning system for 2007. The Cumbre Vieja volcano may be the cause of the next ocean-wide tsunami generated by large-scale flank collapse.

Preface

From a very young age I have been fascinated by the effects of volcanic and seismic activity. I have never witnessed either an earthquake or volcanic eruption. The only volcanoes I have visited are those in Wales and Scotland. Whilst it has been a long time since any of these volcanoes saw activity, the childhood thoughts of them erupting again scared me. I used to have nightmares about volcanoes appearing in my garden, or worse still, under my house. I am sure this dilemma was exacerbated by reading about Paracutin, though the South-east of England is not a likely candidate for the sudden appearance of volcanoes. This fear led to my desire to understand why volcanic eruptions and earthquakes occur. This desire eventually led to my study of S339 (Understanding the continents) and SXG390 (geo-hazards project).

My thoughts for my project initially started with the Indian Ocean Tsunami of Dec 26th 2004. The devastation from this event reminded me of how much we have still to learn about our planet and how poorly equipped we are when it comes to major natural disasters. However, the Indian Ocean is a long way from where I live and I felt I wanted to cover an area much closer to home. I started to consider how we, in Western Europe, would cope if a tsunami were to strike (probably not very well) and how likely such an event was. At first I thought we were rather safe in Western Europe, until I was reminded of the 1755 Lisbon earthquake. Then a news headline caught my eye concerning the Cumbre Vieja volcano on La Palma and large oceanic island collapses. This was quite a shock as up to this point I had thought that a tsunami in the Atlantic was basically unlikely to impossible. Not only was one volcano posing a threat, but as my study continued I read of another two that were candidates for collapse and possible tsunami generation. How wrong my initial thoughts were.

Through my studies I have gained a wealth of knowledge and understanding. The only thing that I have left to do now is to actually visit the island of La Palma (my son wants to go to see the black sand. It looks like my children are now starting to find the same fascination in volcanoes as I have especially as my elder daughter is now fascinated as to why people chose to live on the flanks of active and unstable volcanoes or near major faults). My other ambition in life is to visit the San Andreas Fault in California.

The only problem with geo-hazard study and prediction is the only way to be proven right or wrong is for the event to occur. For such rare events as oceanic island collapses it is possible that the event will not occur in my lifetime and therefore I may never know whether my thoughts and suggestions were correct.

The scope of this project is to outline the research undertaken into the cause and potential effects, to find out how much mitigation of effects has occurred since 2001, what future proposals are being considered and what future actions may be needed.

Introduction to the Cumbre Vieja volcano

In 2001 scientists announced that they believed a volcano in the Canary Islands was in the early stages of instability and that a future eruption may cause as much as 500km^3 of volcano to plummet into the surrounding Atlantic Ocean causing a large (mega) tsunami (Day *et al.* 1999, Carracedo *et al.* 1999, Moss *et al.* 1999). Since then the threat has once again emerged in the news headlines following the earthquake and resulting tsunami in the Indian Ocean on Dec 26th 2004 which generated a 10m tsunami killing over 200,000 people. Other scientists have carried out research in the interim period and have opened up a debate playing down the proposed threat.

Location

The Canary Islands, made up of seven large and two smaller inhabited islands with several smaller islets. They are located off the African coast and are all volcanic in origin (Figure 1). The Cumbre Vieja volcano forms the southern third of the island of La Palma which is situated in the north-west of the Canary Islands and is one of the youngest and most volcanically active of the islands (Figure 2). The volcano rises 6km from the ocean floor with 2km above sea level and has grown sub-aerially over the last 125,000 years. During the 1949 eruption a series of faults appeared and are believed to be indicators of future large-scale flank collapse (Day *et al.* 1999, Carracedo *et al.* 1999 & 2001).

Figure 1. Map of the North Atlantic Ocean. Position of the Canary Islands in respect of the African coast and European coast in the Atlantic Ocean. The Canary Islands are situated off the north-west coast of the Saharan region of the African continent. (Carracedo *et al,.* 1998, & 2001, Vinuela accessed 2005) Map after Moss *et al.* 1999.

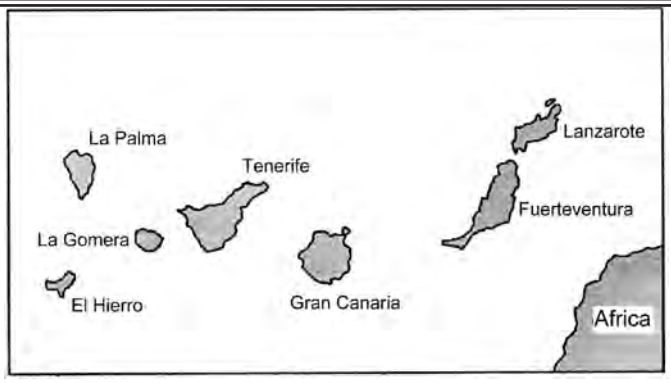

Figure 2. Map of the Canary Islands. The Canary Islands are situated west of the passive margin of the African continental shelf on Jurassic oceanic lithosphere and are believed to exist above a mantle plume though some aspects of hot spot volcanism (Carracedo *et al.* 1998). All the islands are volcanic in origin with the most recent eruptions occurring on Lanzarote, Tenerife, El Hierro, (though the El Hierro eruption is debated) and La Palma. All the islands except La Gomera have experienced volcanic eruptions in historic time (Masson *et al.* 2002). It has been suggested that it has originated from a residual old plume which may explain the absence of some of the hot-spot volcanism characteristics. Lanzarote and Fuevteventura are situated on the continental shelf, with the younger islands resting on the continental rise progressively more westward.

Objectives

1) Describe the geological setting and eruptive history of the Cumbre Vieja volcano.
2) Identify the zone of instability on the volcano and suggest if any future event would cause a catastrophic flank collapse
3) Outline past debris avalanches, debris flows and slumps of the volcanoes on La Palma and other Canary Islands (last 1Ma).
4) Analyse the effect any flank collapse of the Cumbre Vieja volcano would have to the island of La Palma.
5) Examine the mega tsunami computer models based on a large flank collapse of the Cumbre Vieja created by Ward & Day (2001) and Mader (2001) and discuss effects to Atlantic coastal regions.
6) Describe strategies that have been developed to mitigate the effects of a possible collapse of the Cumbre Vieja volcano.

Methodology

The information for this project was researched by this author through refereed journals available from Science Direct such as the 'Journal of Volcanology and Geothermal Research', the Tsunami Society, which produce the journal 'Science of Tsunami Hazards', the Benfield Hazards Research Centre web site, National Oceanic and Atmospheric Association (NOAA) web site and other web searches using google scholar, google, ntlworld, looking for reputable web sites. Key words were used to refine searches. Landslide, Cumbre Vieja, La Palma, mega tsunami, tsunami, pore pressure, and combinations of these. Other articles were searched using citations from refereed journals. Where information was uncertain or difficult to find then personal correspondence with researchers and other students was used.

Geological setting

La Palma is the second youngest volcanic island in the Canarian archipelago, El Hierro being geologically younger though it has not had any recent volcanism. The Cumbre Vieja volcano forms the southern third of the island of La Palma and is the youngest volcano in the archipelago with its most recent sub-aerial eruption occurring in 1971 (Figure 3). It is steep sided with angles typically 20° or more, making it the steepest island in the world, and stands 2km above sea level, 6km above the surrounding ocean floor and has a sub-aerial volume of 123km^3 (Day *et al*. 1999, Henry 1996). La Palma, El Hierro and Tenerife are in the shield building stage, produce alkali basalts, are the most volcanically active in the archipelago and have hosted the most recent large gravitational landslides (Vinuela 2005).

Volcanic History

Before the Cumbre Vieja

La Palma is constructed from a series of volcanoes (Figure 3). The seamount series of La Palma is approximately dated as Pliocene (3-4Ma) and only outcrops in the Caldera de Taburiente. Its lavas have been studied through galerias (excavated water channels extending deep into the northern shield) (Carracedo *et al*. 2001). The first sub-aerial volcanism formed the Garafia volcano overlying the uplifted seamount series which formed between 1.722 and 1.208Ma. About 1.2Ma the Garafia volcano suffered lateral collapse after forming a steep cone with lavas often exceeding 20° and at times as much as 30-35° on its slope (Carracedo *et al.* 2001). The Taburiente volcano formed in the collapse scar of the Garafia and continued to grow rapidly until 560ka when it suffered lateral collapse. Activity of the Taburiente had started as a triple vent system but later volcanism had shifted to be predominantly in the southern rift, the Cumbre Nueva. This

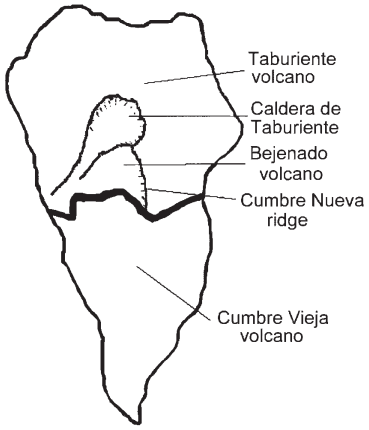

Figure 3. The island of La Palma is made up of three volcanoes. The north of the island comprises of the extinct shield (Taburiente) volcano, current height 2426 m. The Bejenado volcano is nestled between the Taburiente and the Cumbre Vieja creating one wall of the Caldera de Taburiente. The south of the island is comprised of the Strato-cone, Cumbre Vieja, volcano which stands 1949 m in height (Global volcanism program 2005), (map adapted from Moss *et al.* 1999 and Isaac Newton telescope group 2005). The thick black line indicates where the Cumbre Vieja volcano meets the Bejenado and Taburiente volcanoes.

rift grew rapidly, was steepsided and unstable. It collapsed removing approximately 200km^3 of material (Carracedo *et al.* 2001, Day *et al.* 1999). The Bejenado volcano developed in the collapse scar (though there are some discrepancies in the dating and identification of the lava sequences) (Ancochea *et al.* 1994). The Bejenado did not undergo lateral collapse though, since cessation of activity, rainfall has eroded much of the lavas of both the Bejenado and Taburiente forming the Caldera de Taburiente (Carracedo *et al.* 2001). Further south from the Bejenado volcano part of the Cumbre Nueva collapse outcrops. The Cumbre Vieja volcano built up in this remaining collapse scar about 125ka (Day *et al.* 1999, Guillou *et al.*1998).

Holocene

The Holocene saw changes in the eruptive pattern of the Cumbre Vieja. From 125ka to 20ka a triple vent system existed (Figure 4). From 20ka the topography of the volcano has been dominated by a single north-to-south rift, which has propagated slightly northwards, about 2-3km from the summit. This ridge continues for a few kilometres offshore to the south before bending to a southeasterly direction (Day *et al.* 1999). There is no evidence of a central summit crater feeder complex as is found on many other oceanic island volcanoes. Petrology of volcanics suggests that the basic and intermediate magmas are erupted directly from reservoirs in the oceanic lithosphere below the base of the La Palma edifice (Day *et al.* 1999). Whilst this led some scientists to believe that the volcano had only a single rift system and was most likely a southern extension of the Cumbre Nueva (Alfonso 1974, Ancochea *et al.* 1994) Carracedo (1994 & 1996) noted the vent density and distribution suggested much weaker NW and NE rift zones giving rise to a triple rift system and a separate volcano. Since 7ka there have been no eruptions on the NE rift. This abandonment appears to be unique in the history of the Cumbre Vieja and suggests an asymmetry in the structure of the volcano since

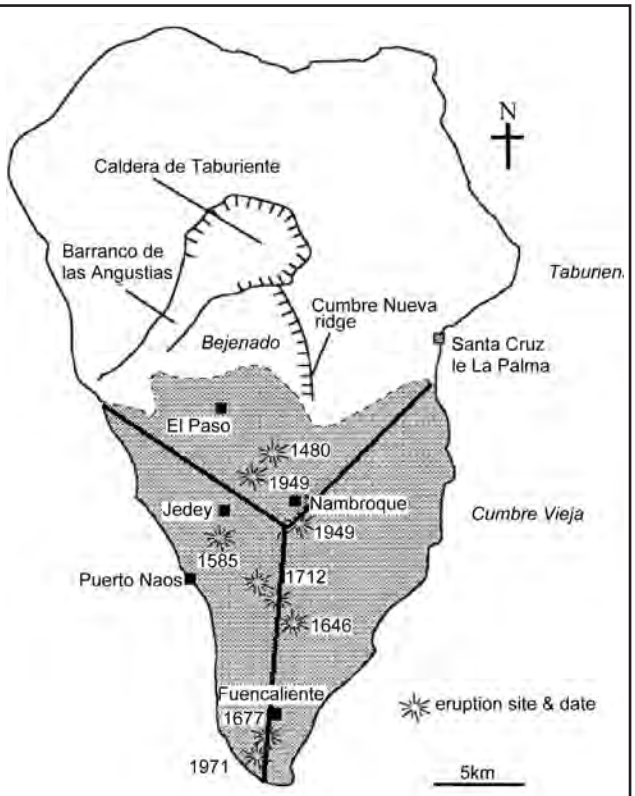

Figure 4. Map of La Palma showing the Cumbre Vieja volcano in grey. The black lines are a schematic representation of the inferred triple (Mercedes star) rift that existed between 125 -20ka. From 20ka activity on the NE arm of the rift ceased and the NW arm has experienced less activity than the southern arm. Prior to 125ka the activity on the NE arm had been greater than the NW or S arm (Day *et al*. 1999). The Cumbre Vieja is the most active volcano in the Canary archipelago and has experienced seven historic eruptions, in 1480, 1585, 1646, 1677, 1712, 1949 and 1971 (Moss *et al.* 1999). Return periods for eruptions are between 22 years and 237 years giving average return period of every 100 years. There are about 120 volcanic vents distributed along the crest (Isaac Newton telescopes group 2005). Map adapted from Moss *et al.* 1999 and Day *et al.* 1999)

7ka, indicating that the western flank is separating from the rest of the volcano thus, increasing instability (Carracedo 1996, Day *et al.* 1999).

Historic eruptions

There have been seven eruptions in historic times, three of which occurred at the summit, 1646, 1712 and 1949 (Figure 4).

1949 eruption

The 1949 eruption followed a period of over two hundred years of dormancy and saw eruptions from three different vents, between 24th June to 30th July with up to two vents open at any one time (White *& Schminke* 1999, Klugel *et al.* 1999). The eruption was preceded by eleven years of 'felt' seismicity. A fault developed between two of the vents originally photographed and documented by Rubio on and after July 6th 1949 (Figure 5; Rubio 1950). The fault measures 4km in length, is concave, and has slipped westward by up to 4m. The faulting appears to be unique to the 1949 eruption with no evidence being found of faulting during past eruptions. No east-facing faults have been found suggesting

the event is asymmetric and not due to grabben formation (Day *et al.* 1999). This,along with the absence of fumarolic evidence indicates that it is not the result of dyke emplacement even though it extends between two vents open during the 1949 eruption (Carracedo *et al.* 1999). The greatest felt seismicity of the eruption was recorded on the 1st and 2nd July but did not tie in with any eruptive episodes, suggesting a possible date for the fault opening. As there were no seismometers in place during the eruption seismic strength and foci have been extrapolated from the local population's recollection on La Palma and other Canary Islands. From this information Day *et al.* (1999) deduced that the earthquakes were most likely shallow and located in the upper part of the volcano edifice.

Figure 5. Photo (Day *et al.* 1999) of part of the 1949 faults. The faults appeared during the 1949 eruption and are believed to be the surface feature of a larger fault system which may cause up to 500km^3 of the edifice to detach and slide into the sea. It is believed that the surface expressions are linked to a steeply dipping (at 60° or more) fault at greater depth with a number of bends and jogs along its length but the movement is generally dip/slip normal faulting (Day *et al.* 1999). Permission to reproduce granted.

1971 eruption (Teneguia)

Twenty-two years after the 1949 eruption, the volcano was once again active. On 27th October 1971 an eruption started at the extreme south of the island following days of seismicity. Fissures appeared close to the epicentres of the 1949 pre-eruption seismic activity and gas started to escape.

The eruption created six vents erupting lava fountains, lapilli, bombs, scoria, pyroclasts and lava flows which reached the sea. Their subsequent spatter cones grew and in some cases engulfed other cones which subsequently collapsed. The eruption continued until midnight 18-19th November 1971 when all activity and seismicity stopped (Global volcanism program/La Palma/ activity reports 2005). The eruption caused no further movement of the 1949 fault (Day *et al.* 1999).

Reasons for instability

Inter-eruptive movement

During the 1990s geodetic monitoring was carried out on the Cumbre Vieja. Electronic distance measurement (EDM) was used in 1994, 1996 and in 1997 EDM was combined with global positioning satellite (GPS). Scientists wanted to find out if the fault was unstable and moving in the same way as the faults on other oceanic island volcanoes such as Kilauea and Etna. From the readings taken at various locations at the summit and on the western flank a 1cm a year movement was noted but fell within error margins and so it was concluded that no further movement had occurred along the 1949 faults and that the faults were stable during inter-eruptive periods (Moss *et al.*1999). If the fault is stable during inter-eruptive periods then it would be necessary to establish what future event would trigger a catastrophic failure.

Beneath the volcano

The Cumbre Vieja has built up in the collapsed scar of the Taburiente/ Cumbre Nueva. The steep-sided nature of the volcano and the rapid growth mainly consisting of volcanic rubble situated on top of what is believed to be loose sediments, gives rise to instability (Figure 6).

Pore pressure

As there is no movement during inter-eruptive periods or during the 1971 eruption, something else is needed to trigger a collapse. Day (1996) suggested that pore pressure may be such a trigger. Water may become heated with a fresh intrusion of magma causing a build up of pressure which could destabilise the flank (Elsworth & Day 1999). Pararas-Carayannis (2002) suggested this was unlikely due to the porous nature of the volcanoes. Day (1996) proposed that water could build up between the impermeable dykes and demonstrated, through galerias access, that the inside of the volcano hosts a large quantity of water (BBC TV Horizon 2001).

The 1949 eruption followed a period of over two hundred years of dormancy. During this period ground-water levels will have had good opportunity to build up which is likely to be a contributory factor to the fault surfacing. The fault is likely to have been developing over many eruptions, finally surfacing in 1949. The 1971 eruption occurred twenty-two years later which would have given little opportunity for ground water build up between dykes. This, along with the southerly location of the eruption, helps to explain why this eruption caused no further movement of the fault or new faults to appear. The longer the period between eruptions, the more likely catastrophic failure is likely to occur at the next eruption due to ground-water build up.

Rising sea levels or an increase in rainfall, will also contribute to ground water build up between dykes (Figure 7).

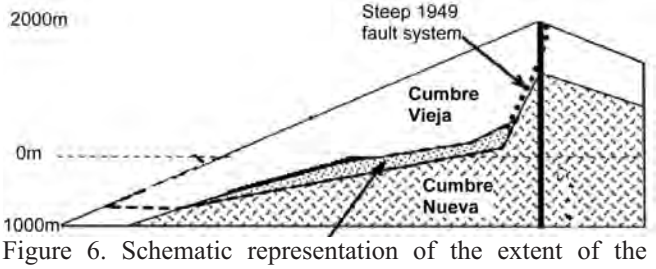

Figure 6. Schematic representation of the extent of the inferred fault and the possible excavation from a future collapse. An unconformity exists between the Cumbre Nueva collapse scar (which is likely to consist of loose sediments), and the current Cumbre Vieja. It is believed that a future collapse would occur at this point (Diagram adapted from Day *et al.* 1999).

Past landslides in the western Canary Islands

Whilst the Cumbre Vieja has not suffered lateral collapse during its life, other Canary Island volcanoes, including two on La Palma, have. There have been fourteen landslide events in the last 1Ma around La Palma, El Hierro and Tenerife giving a return period of approximately 100ka. These comprise debris flows, debris avalanches and slumps but most are debris avalanches (Figures 8 & 9 and Table 1, Masson *et al.* 2002). There are some discrepancies concerning the size, number and dates of landslide events. Offshore evidence often shows a break up of debris, suggesting multiple slides occurring in close succession with more recent dates than onshore evidence (Masson *et al.* 2002, Wynn & Masson 2003, Carracedo *et al.* 1999 & 2001).

The last collapse in the Canary islands was the El Golfo collapse on El Hierro 15ka (Masson *et al.* 2002) (Wynn & Masson 2003). However, Carracedo *et al.* (1999) found onshore evidence suggesting that the collapse occurred 120ka. They suggest the possibility of a subaerial collapse 120ka followed by a later underwater collapse 15ka. However, Masson *et al.* (2002) found no offshore evidence of a second collapse.

The potential effects of volcanic collapse

Landslide behavior

When calculating the potential behaviour of volcanic collapse on the scale of La Palma, scientists have turned their attention to smaller edifice collapses and based their hypotheses on them. There are no records of larger landslides due to their absence in historic or near pre-historic times.

Mt St Helens

On May 18th 1980 Mt St Helens' north flank collapsed following an earthquake of magnitude 5.1. This collapse was followed quickly by the eruption. The avalanche cascaded down the north flank and one tongue entered Spirit Lake to the north-east. The collapse occurred in one catastrophic event and entered the lake causing the water to rise nearly 100m and to surge on the opposite bank 250m over ridges stripping trees and soil. Despite evacuation of the area 57 people and much wildlife died during the eruption (Corcora 2003).

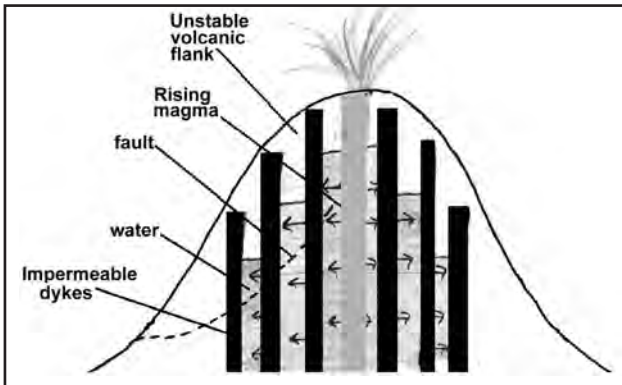

Figure 7. Schematic representation of pore pressure inside a volcano. As magma rises, water trapped between impermeable dykes heats up and the resulting pressure puts strain on the surrounding edifice. In the case of the Cumbre Vieja volcano a fault already exists in the western flank which could be further destabilised by this pressure. During a future eruption, pore pressure may build up sufficiently to cause the fault to fail and result in a catastrophic landslide.

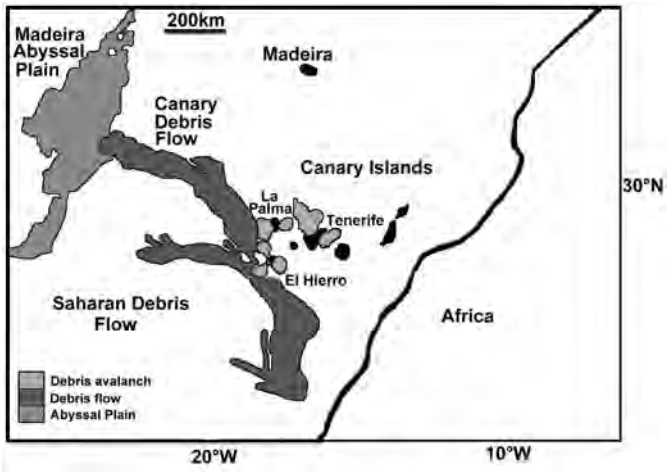

Figure 8. Map showing the most recent landslides in the Canary Islands and their run outs. Information was gathered in waters up to 4000m depth, using an EM12 multibeam system, TOBI 30 KHz side scan sonar images. Initial slumps and avalanches have since been dispersed as far as the Madeira abyssal plain in debris flows. (Adapted from Masson *et al.* 2002)

Lituya Bay

On July 8th 1958 Lituya Bay, in Alaska, experienced a 7.5 magnitude earthquake along the Fairweather fault with the epicenter near Lituya Bay. A large landslide was triggered by the quake cascading down the mountain side into Lituya Bay. A mega-tsunami ensued with wave run-ups of 520m which stripped trees and soil off the opposite side of the bay leaving behind bare rock. (A mega tsunami is considered to be a tsunami of greater height than that created by an earthquake.)

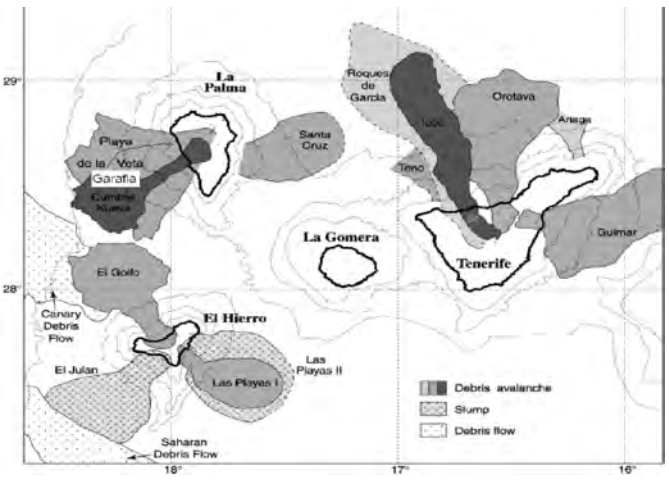

Figure 9. Landslides from the last 1Ma in the Canary Islands. Most are debris avalanches, though two on El Hierro are possibly slumps. Two of the Tenerife slides are thought to have been in the region of 500km^3 in volume and the Playa de la Veta complex on La Palma, (which is believed to have occurred as a single catastrophic slide by Carracedo *et al.* 2001), may have had a volume greater than 650km^3 (Adapted from Masson *et al*. 2002). The Santa Cruz debris avalanche is apparent offshore but has no collapse scar onshore so its origins are uncertain. (Carracedo *et al.* 2001).

Island	Landslide	Type	Area (km^2)	Volume (km^3)	Height (m)	Runout length (km)	h/l	$A/V^{2/3}$	Age (ka)
El Hierro	El Golfo	Debris Avalanche	1500	150–180	5000	65	0.076	53	13–17
	Las Playas 1	? Slump	1700	?	?4000	?50			176–545
	Las Playas II	Debris Avalanche	950	<50	4500	50	0.090	70	145–176
	El Julan	? Slump or Debris Avalanche	1800	? 130	4600	60	0.077		>160
	Canary	Debris Flow	40,000	400	1450	600	0.0024	740	13–17
	Saharan	Debris Flow	48,000	1100	3200	700	0.0036	450	60
La Palma	Cumbre Nueva	Debris Avalanche	780	95	6000	80	0.075	37	125–536
	Playa de la Veta	Debris Avalanche complex	2000	? 650	6000	80	0.075	27	?800–10
	Santa Cruz	Debris Avalanche	? 1000	?	?3500	50	? 0.070		?>900
Tenerife	Icod	Debris Avalanche/Flow	1700	? 150	6800	105	0.065	60	150 170
	Orotava	Debris Avalanche	2100	? 500	6600	90	0.073	33	540–690
	Roques de Garcia	? Debris Avalanche	? 4500	? 500	7000	130	0.054	71	?>600
	Anaga	? Debris Avalanche	?>400	?	>3500	?	?		≫1000
	Guimar	Debris Avalanche	1600	120	>4000	> 50	?	66	780 840

Table 1. Table showing details of the 14 giant landslides that have occurred over the last 1Ma. There are discrepancies over the age and size of many of these slides including the Cumbre Nueva collapse. The above table suggests that the volume of this avalanche was only 95km^3 using offshore evidence, (Masson *et al.* 2002); yet onshore evidence suggests a volume of 200km^3. Further analyses of both onshore and offshore evidence are required to establish the size and nature of these events in order to predict future events. Reprinted from Earth Science Reviews, vol 57, D G Masson *et al. 2007,* Slope failures on flanks, Western Canary Islands, pp1-35, with permission from Elsevier.

Two survivors were lifted in their boat for several metres. Two other boats were destroyed and their occupants killed. The tsunami washed over the headland at the entrance to the bay and dissipated in the Pacific Ocean (Mader & Gittings 2002, BBC TV, Horizon 2001). The Lituya Bay tsunami has been used by scientists as a basis for tsunami computer models.

Calderas

The avalanches above created locally devastating tsunamis but were met by a steep-sided bank, which aided in the dissipation of the waves, or were land locked. Neither of the above examples can explain how an edifice failure would behave in the Atlantic Ocean where the next landfall to the west of La Palma is the American and Bahamian coast. Pararas Carayannis (2002) and Mader (2001) believe that any tsunami created by edifice failure will dissipate in open ocean. Pararas-Carayannis bases his beliefs on comparisons with caldera formation, using Santorini and Krakatoa as examples. Both these volcanoes collapsed after days of erupting vast quantities of volcanic material which caused the weight of the remaining volcano to collapse into the now empty magma chamber. However this type of collapse is not a good example for modeling the La Palma edifice failure as caldera formation occurs in several stages, not one catastrophic event and calderas collapse in on themselves causing water to rush into the void created before bouncing back out. Edifice failure causing avalanche will push the water in front of it out of the way causing it to lift, hence, causing a large wave. However, using calderas as a comparison, both these collapses involved much less material (about one hundred times less) than is suggested for La Palma but were able to wash over many of the surrounding islands causing devastation. Small tsunamis were witnessed on the opposite sides of the ocean/sea and in the case of Krakatoa, small tsunamis were documented in other oceans including the English Channel, though this is more likely to be as a result of air pressure changes rather than wave propagation. (Pararas-Carayannis 2002 & 2003). Caldera formation demonstrates the ability of resulting tsunamis to travel across oceans though the wave height and length is likely to be less than that created by edifice failure (Figures 10, 11 & 12).

Modeling the La Palma collapse.

Through studying the behaviour of passed edifice failures it is possible to postulate how a large scale flank collapse of the Cumbre Vieja will behave. Mt St Helens, and other volcanic edifice failures that have been studied, have collapsed in a single event during volcanic and seismic activity (seismicity on volcanoes is often linked to a fresh intrusion of magma). It is believed that a future eruption will trigger catastrophic failure but not necessarily the next eruption. It is also believed that when failure occurs it will be in a single event (Day *et al.* 1999, Moss *et al.* 1999, Carracedo *et al.* 1999) and not in multiple events over several days as suggested by Wynn & Masson (2003) and Pararas-Carayannis (2003).

Potential effects of a collapse to La Palma

The island of La Palma's population of 80,000 are all likely to be affected by any gravitational collapse whether or not they live on the unstable flank (Figure 13).

Landslide effects

For the worst case scenario the proposed area of instability includes land in the administrative districts of El Paso, Tazecorte, Los Llanos and Fuentcallente. The populations of these areas are estimated to be about 30,000. Those not directly on the landslide path

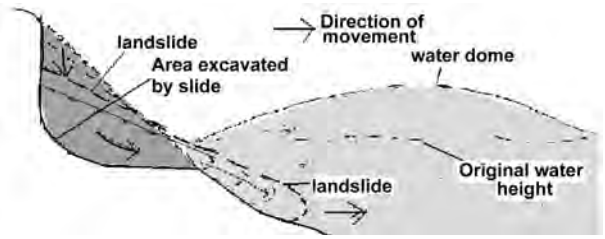

Figure 10. Edifice failure. As the edifice slides toward the sea the sea water is forced out of the way causing it to dome up in front of the landslide. This will cause a trough to form behind the dome generating a tsunami. The height of the water dome will be determined by the size and speed of the landslide.

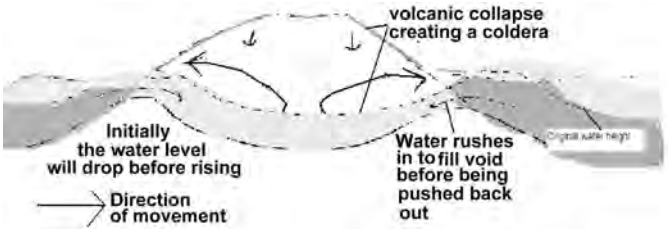
volcanic collapse creating a coldera
Initially the water level will drop before rising
Direction of movement
Water rushes in to fill void before being pushed back out

Figure 11. Caldera formation. As the magma chamber empties the weight of the volcano is too great to be supported. The edifice collapses in creating a void. Sea water rushes into the void generating a trough in the surrounding sea. The force of the water entering the chasm causes it to splash back creating a dome, generating a tsunami. The size of tsunami waves are determined by the speed and size of collapse but are likely to be smaller than the equivalent size and speed generated from landslide.

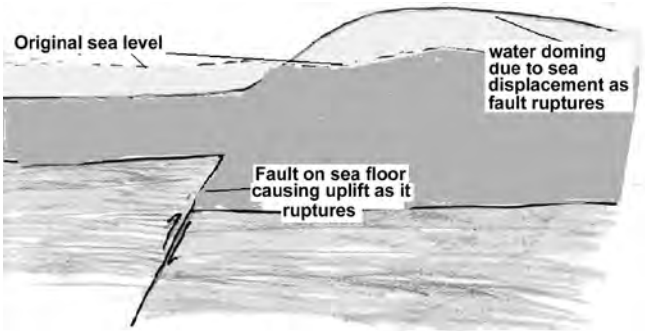
Original sea level
water doming due to sea displacement as fault ruptures
Fault on sea floor causing uplift as it ruptures

Figure 12. Fault rupture. (As a comparison to edifice failure-generated tsunami) Tsunamis are frequently generated by earthquakes when a fault ruptures at the surface. The displacement of the sea floor pushes the sea upward causing water doming and troughing. The size of a tsunami wave is determined by the amount of sea floor uplift that has occurred. Generally less than 10m. The Indian Ocean tsunami produced a 10m high tsunami with run ups of about 20m. Landslides and calderas have the potential to generate much larger tsunami waves as was demonstrated by the landslides of Mt St Helens and Lituya Bay. Tsunami waves of greater height than those generated by earthquakes, (>10m) are sometimes referred to as 'mega tsunami'

may still suffer ground movement as the land is pulled along with the slide. Any collapse could lead to significant loss of life as well as loss of property and farm land. Economic costs are likely to be high (Figure 13).

Mega tsunami. Modelling the potential

Computer models

Whilst the landslide will have devastating effects on the western flank, the rest of La Palma will also face devastation. Using data and modelling techniques tried out on smaller volcanic edifice collapses, Ward & Day (2001) (Figure 14), and Mader (2001) have developed computer models to estimate wave propagation, speed and height following collapse. The models were based on worst-case scenario of 500km^3 entering the sea as a single event at 45-100m/s, for 600s. Data was collected from studies carried out using the SWAN code which solves the nonlinear long waver equations (Mader 2001).

An initial wave of 650m at a 20km radius with a 30-40km wavelength and 3-4 minute period was predicted (Mader 2001). Ward & Day (2001) predict the water dome above the collapse would be over 900m. This dome would spread out and subside with a trough developing behind it. After 50km of travel the wave would drop to 500m and would have outrun the disintegrating landslide. Subsequent waves are expected to be larger than the first wave.

Mega tsunami in the Atlantic Ocean

Tsunami waves would encircle the island of La Palma hitting the capital Santa Cruz, on the eastern side between 5-10 minutes after with an initial wave height of about 100m. Subsequent waves may be as large as 200m. Waves >200m in height are predicted to strike the western Canary Islands after 10 minutes and strike the other Canary Islands from 15-60 minutes. Waves 50-100m in height are predicted to hit the west coast of Africa about one hour after the slide begins. Shoaling of waves as they approach the west Saharan coast will slow the leading edge of the wave causing the dome to rise (Ward & Day 2001, Mader 2001).

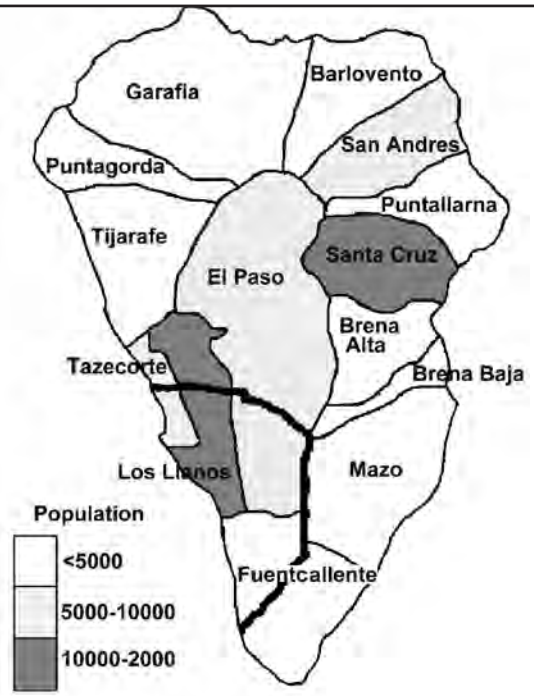

Figure 13. Geographical map of La Palma showing the populations of the 14 administrative districts. The inferred unstable zone includes parts of the populated areas of Tazecorte, Los Llanos, El Paso and Fuentcallente. These areas are also key farming districts based on the fertile flanks of the Cumbre Vieja volcano and popular regions for holiday makers, though tourism on La Palma is not as well developed as it is on some Canary Islands (Isaac Newton telescopes 2005). Black line represents the extent of the fault on land. The toe of the fault surfaces below sea level. (Adapted from Day *et al.* 1999.)

Mader (2001) predicts that the tsunami would disperse quickly and by the time it reached the western coasts of Europe it would be <10m in height. Ward & Day (2001) also predict waves of 5-7m making landfall on the west coasts of Spain and England. Europe would be spared much of the tsunami impact, being shielded by La Palma itself.

Whilst the models created by Ward & Day (2001) and Mader (2001) are similar in their suggestions of tsunami for the Canary islands and Europe and for their overall travel times, the effects suggested for the east coast of America and the Bahamas is considerably different. Mader (2001) believes that the tsunami will dissipate as it crosses the Atlantic and would hit the east coast of America with a wave between <1-3m. He suggests that even with shoaling this would not present a significant threat. However, Ward & Day (2001) do not believe that the wave would undergo significant dispersion and that the initial wave would not be the largest. They suggest that the initial wave height striking the north and south-east coast of America would be >10m with subsequent waves of 15-20m. After nine hours of travel, Florida could face waves >20-25m in height (Figure 14). The run up is likely to extend several kilometres inland and tsunamis can also propagate up rivers from their estuaries causing damage away from coastal areas (Ward & Day 2001, Mader 2001).

Past mega-tsunami

Edifice failure and mega tsunami appear a very daunting possibility and difficult to believe because there are no witnessed experiences of anything near the scale suggested. Past volcanic edifice collapses provide insight into how landslides and resultant tsunamis behave in the local vicinity. Onshore and offshore evidence demonstrates that large edifice failures have occurred in the past but do not provide evidence of past mega tsunamis. In 1996 and 1997 scientists studying the Bahamian archipelago observed large boulder deposits between 100-1000m^3 in size on North Eleuthera and chevron-shaped ridges in the windward margins of the Bahamian Islands. They appear to have been laid down about the same time between 75 and 120ka and the group of scientists postulated that they had been created by massive waves. Initially they assumed they were tsunami deposits but quickly ruled out this possibility due to no tsunamogenic event occurring at the time of formation. They instead concluded that they were created by massive storm waves at the end of last interglaciation period caused by falling sea levels (Hearty 1997, Hearty *et. al* 1998). The ridges all strike NE and during their research, Hearty *et al.* (1998) searched for tsunami generating forces within the Bahamas but not further afield. The El Hierro collapse occurred between 110-120ka by onshore evidence, which ties in with the deposition of the giant boulders and chevron ridges. A tsunami caused by the deposition of 150-180km^3 of edifice material entering the Atlantic Ocean would wash over the low-lying Bahamas and could have been responsible for the deposits. El Golfo on El Hierro faces NE from the Bahamas and so is correctly positioned (BBC TV

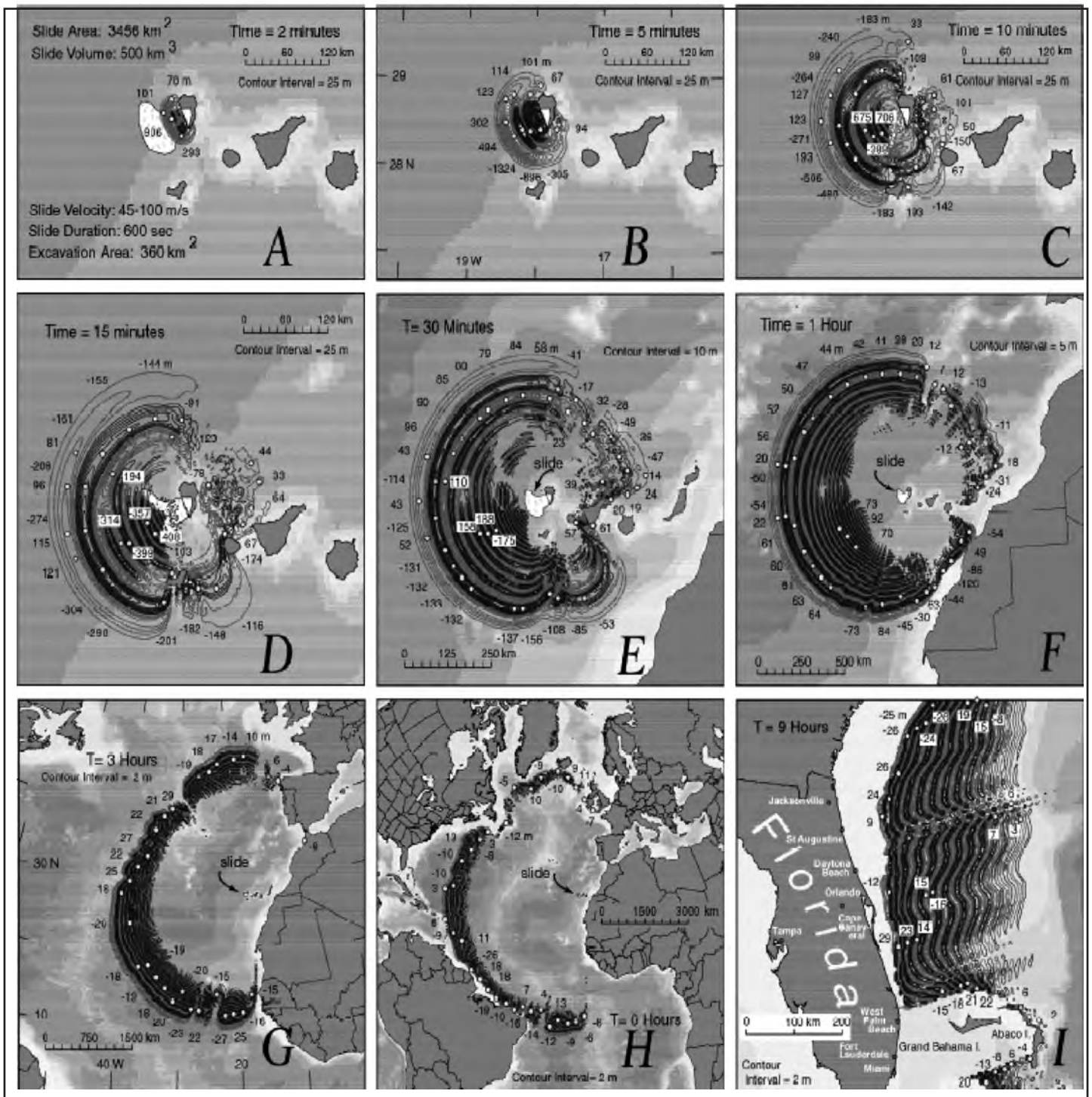

Figure 14. Projected wave heights following a large gravitational collapse of the Cumbre Vieja. Slide volume estimated as 500km^3, travelling at 100m/s travelling for 600s. Calculations are based on Ward and Day's computer model (2001). The computer model has been updated to include ocean floor topography and is available from http://es.ucsc.edu/~ward/. Light grey indicates wave peaks and black indicates wave troughs.

Horizon 2001, Day pers comm.). It is likely that these deposits are evidence of a past mega tsunami in the Atlantic. Similar deposits have also been found in the Pacific Ocean believed to have been caused by massive landslides in the Hawaiian Islands (many of which are larger than suggested for La Palma, Moore & Moore 1984, McMurtry *et al.* 2004), around the Australian Indian ocean coast, believed to have been caused by the Reunion collapse (which was the last massive collapse, Kelletat and Scheffers 2003) and in the Canary Islands (McGuire *et al*. 2003).

Monitoring the Cumbre Vieja

Geodetic monitoring

During 1994, 1996 and 1997 geodetic measurements of the edifice were carried out to establish whether there was any movement during inter-eruptive periods. No movement was detected outside the error margins and so it was proposed that the volcano was stable between eruptions. Future occupations of the network will be required to confirm stability (Moss *et al.* 1999).

Seismic monitoring

The Cumbre Vieja currently has very little monitoring. One three-component station is positioned at the centre of the Cumbre Vieja ridge (WOVO 2005) and a single-component station at Fuentcalliente in the south (Day pers comm. 2005). These seismographs will give early warning of seismic activity, signalling a new intrusion of magma when more instrumentation could be installed. Volcanoes do not erupt without warning. Seismic activity, fumarolic activity, increase in ground and water temperatures often precede eruptions as magma forces its way through rock. This activity intensifies and becomes more frequent prior to eruption. Whilst this offers an early warning of impending eruptions, Mt St Helens demonstrated how edifice failure cannot be predicted.

Future Proposals

The western flank may fail with little precursory deformation giving limited warning for evacuation. Continuous monitoring of the volcano may be necessary. Advances in technology allow the monitoring of volcanoes with reduced risks to the scientists carrying out the surveys. Interferometry Synthetic Aperture Radar (InSAR) uses satellite technology to record topography and deformation of volcanic edifices. Once in place, monitoring can be carried out without the need for scientists to be on the volcano. The Benfield Hazard research centre have proposed the use of InSAR on the Cumbre Vieja as has been used on Tiede, Tenerife (Fernandez *et al*. 2003). (Fernandez *et al*. (2003) also published InSAR images of La Palma). This would establish if there were any inter-eruptive movement and would allow for safe monitoring during any future seismic and volcanic activity (Day pers comm. 2005). The next eruption may not be the one that causes the edifice to fail or may result in another aborted failure as occurred in 1949. This could lead to a number of false alarms which will reduce public belief in the threat. A greater understanding of the events that have occurred to de-stabilize the flank is essential.

Monitoring the Atlantic (Tsunami risk)

Atlantic tsunami warning system

NOAA (National Oceanic and Atmospheric Association) plans to have in place seven buoys by 2007 for the Atlantic tsunami warning system in response to the Indian Ocean tsunami of Dec 26th 2004 (NOAA web page 2005) (Figure 15).

Figure 16 is a diagram showing the workings of the DART warning buoys. A signal is sent between the base station situated on the ocean bottom and the buoy. As the buoy bobs around in the waves the distance between the two is measured. This measurement is transmitted to a satellite which also pinpoints the exact location of the buoy using GPS (global positioning satellite). A tsunami will be recognised by the upward or downward movement of the buoy in relation to the base unit. The wavelength of a tsunami is longer than atmospheric- generated waves and so the wavelength duration will be an indicator of a tsunami. Tsunamis are much smaller in the open ocean than on the continental shelf and so may not be noticed by ships. The final run up waves could be much larger and damaging. (NOAA web site 2005).

Educating the public

Tsunami warning systems may provide some advance warning but the public need to be more aware of tsunamis. During the 2004 tsunami in the Indian Ocean survivors reported people rushing to the sea to stare at the spectacular sight of the sea withdrawing. Those who knew about tsunamis fled as they expected several large waves. Those who remained died. The people near

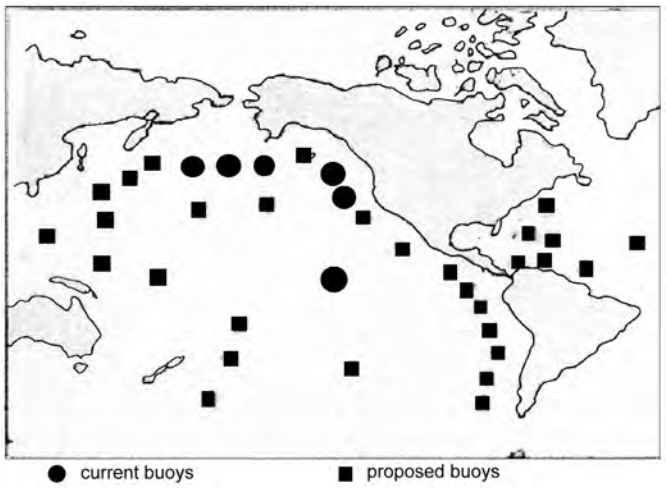

Figure 15. Map showing the position of existing tsunami monitoring (DART) buoys and the position of future proposed buoys. There are seven buoys planned for the Atlantic Ocean. Adapted from NOAA web site (2005).

the epicentre who felt the earthquake failed to flee to higher ground as is so often seen in countries, such as Japan, which experience earthquakes and subsequent tsunamis more frequently. Tsunamis in the Atlantic are very rare, the last ocean-wide tsunami occurring in 1755 with the great Lisbon earthquake. Most people living in the Atlantic coastal regions will not have experienced a tsunami and many would be ignorant of their warnings. Without

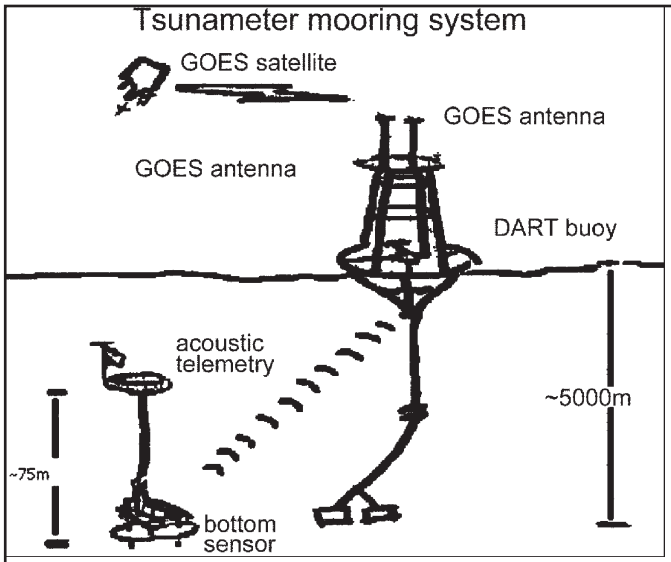

Figure 16. Diagram showing the workings of the DART warning buoys. A signal is sent between the base station situated on the ocean bottom and the buoy. As the buoy bobs around in the waves the distance between the two is measured. This measurement is transmitted to a satellite which also pinpoints the exact location of the buoy using GPS (global positioning satellite). A tsunami will be recognised by the upward or downward movement of the buoy in relation to the base unit. The wavelength of the tsunami is longer than atmospheric-generated waves and so the wavelength duration will be an indicator of a tsunami. Tsunamis are much smaller in the open ocean than on the continental shelf and so may not be noticed by ships. The final run-up waves could be much larger and damaging. Adapted from NOAA web site 2005)

education the response during the Indian Ocean tsunami is likely to be seen even with adequate warning from buoys.

Future actions

As well as a tsunami warning system and public awareness, evacuation procedures will need to be in place. An edifice failure of the Cumbre Vieja will give America about six hours' warning assuming they are notified as soon as it occurs. The positioning of the buoys will only give a few hours notice, certainly not sufficient time to evacuate the whole of Florida or the Bahamas even with a good evacuation plan in place. Whilst the UK will have significantly smaller waves a collapse occurring during the summer months when the south-west coast receives a large number of tourists could be disastrous during evacuation. Many of the roads are narrow and easily congested. Some of the smaller isles such as the Scilly Isles may be completely cut off. Coastal cliff regions may be eroded by the impact of large waves. Without adequate evacuation plans many lives could be lost.

Communication networks will also need to be in place. The 2004 Indian Ocean tsunami-causing earthquake was detected by the Tsunami warning centre in Hawaii but messages warning of the tsunami were sent out too late for action. Even with earlier warning there was no communication network capable of warning those in affected areas. Tsunami warning is not just about detecting possible waves but also about notifying those in immediate danger and warning rescue services to be on standby. A good communication network is needed.

Coral reefs

Coral reefs provide a natural barrier to sea waves. Preservation of current coral reefs and encouragement of growth of new coral may provide some protection from tsunamis particularly if waves are smaller than those predicted. A correlation between damage to coastal regions and the depletion of coral reefs was noted in the Indian Ocean following the 2004 Indian Ocean tsunami. (Geological Society 2005).

Conclusion

The Cumbre Vieja volcano, situated off the west coast of Africa, is believed to be in the early stages of collapse. During the 1949 eruption a 4km long concave fault surfaced on the western flank of the Cumbre Vieja volcano. This was a unique event in the life of the volcano suggesting that the western flank has de-stabilized. The fault is believed to be the surface expression of a much larger fault which extends from the summit to below sea level off the western coast. The fault does not appear to show any a-seismic creep and is deemed stable during inter-eruptive periods. A future summit eruption and pore pressure build up is believed to be the most likely trigger for a future failure of the fault which could send as much as 500km^3 of edifice into the surrounding Atlantic Ocean. It is believed that the landslide would break off as a single event and travel into the sea before breaking up. This could generate a water dome up to 900m in height which would spread out into the Atlantic Ocean as a 'mega' tsunami. Large waves would wash up on Atlantic coastal regions causing vast destruction of land, property and life.

Geodetic monitoring during the 1990s concluded that the flank was not of significant threat during inter-eruptive periods, but also suggested that future monitoring should be carried out to confirm this. To date no further monitoring has occurred though suggestions have been made to use InSAR monitoring. Proposals for a tsunami warning system for the Atlantic Ocean have also been proposed to be in place during 2007. However, adequate communication, public awareness and monitoring of the volcano will also be required. Evacuation plans and civil defence plans need to be created and practised in all countries likely to be affected. The creation and preservation of coral reefs may lessen the effect of any tsunami to coastal regions.

The Cumbre Vieja volcano poses a threat to Atlantic coastal regions through edifice failure and may be the cause of the next ocean-wide mega tsunami.

Acknowledgements

I would like to acknowledge the help and support I have been given by my family especially my children who have had to put up with me talking about volcanoes and tsunamis for a number of months as well as having to wait hours on end to use the computer. They are still optimistic of a holiday to La Palma.

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Finally, I would like to thank my tutor for the time and effort she has given. I think she'll be glad to see the back of my punctuation errors. Without her suggestions and support my project would not have been anywhere near as good as it is.

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Author

Tracy Chamberlain BSc Hons (Open) is a single parent with two teenage daughters and a son (aged 10) living in Hertfordshire. She works as a first aid trainer and is currently studying S260, SXR260 and S182. When she started her degree she had no real plan but as she progressed she decided that teaching would be a good move (though tempted by the MSc geohazards course). She found it hard working on her poject as she has never been close to an active/dormant volcano and longed to visit La Palma. It is her ambition to get to La Palma, visit other volcanoes and the San Andreas Fault. She is preparing to start a flexible PGCE course with the Open University.

Book reviews

Introduction to Mineral Exploration ed. Charles J Moon, K G Whateley, and Anthony Evans, 2nd edition, 2006, Blackwell, pp 480, £34.99 (paperback) ISBN 1405113170.

Not all symposium talks remain in the mind as really having been worth listening to; when they do, they've often been given by people out there in the field, who have to sell their expertise to go on making a living. One such was Chris Carlon's Frontiers for Mineral Exploration at Telford in 2000 – but though the talk excited me I've hardly given the subject a thought since. This thorough volume – cheap at the price – originating in courses given at Leicester University, is of course too full for casual reading up the subject, but looks an absolute must for anyone wanting to address it seriously.

About two thirds of the text is "Principles" – clearly divided into Ore, Mineral Economics, and Mineral Exploration; The Mineralogy of Economic Deposits; Mineral Deposit Geology and Models; Reconnaissance Exploration; From Prospect to Prefeasibility; Remote Sensing; Geophysical Methods; Exploration Geochemistry; Mineral Exploration Data; Evaluation Techniques; and Project Evaluation. The rest consists of six case studies: aggregates in Leicestershire, lignite in Turkey, gold on the Rand, sulfide [sic] in Ontario, precious metals in Nevada, and diamonds in the Canadian Arctic.

Useful internet links are given at the end, as well as a comprehensive bibliography. The pictures, figures, and maps are in black and white, but of good quality and intelligible.

"A detailed understanding of the geology of mineral deposits is required to explore effectively for them." Unfortunately, "this is beyond the scope of this volume". So there's not too much on inferred lithotectonic settings, the origin of hydrothermal fluids, and other strictly geological models.

It's good to know that "in countries with large unexplored areas and liberal land tenure laws, e.g. Canada, Australia and Brazil…you can still meet the grizzled [individual] prospector or garimpeiro. Although they usually lack the sophisticated training of the corporate geologist, this can be compensated for by a keen eye and the willingness to expend a little boot leather." (Readers who had the right children's books will remember "Squashy Hat" in Pigeon Post!)

It's not so good to learn of the decline in the teaching of mining related subjects in recent years, especially at universities in Europe and North America.

Philip Clark, BSc (Hons) Open

Introduction to the Study of Dinosaurs second edition by Anthony J Martin, 2006, Blackwell Publishing Ltd, 560pp, (paperback) £39.99, ISBN 1405134135.

What a great book! With 560 pages and weighing 1.75 kg it is no mean tome but on an initial review it showed that it is well set out, full of lovely coloured pictures and prints and diagrams. Each chapter has an extensive bibliography and there are a series of discussion questions at the end of each chapter. The book also uses the scheme of placing Tables of information in clear purple boxes and Summaries of each chapter in pink boxes.

At first glance this appears to be a text book designed for younger children but on reading the chapter contents it is apparent that it is a much more rigorous study of dinosaurs. The initial chapters define dinosaurs, give an overview of the scientific methods used to study them, the History of Dinosaur Studies and then places them in to the geological context. This latter chapter is interesting as it sets out the field equipment, the information conveyed on topographic and geological maps, and gives a clear overview of the theories of superposition and stratigraphic sequences. It also looks at isotopic dating and plate tectonics. Finally it examines the anatomy and classification of dinosaurs.

Up to this point it is a general book about dinosaurs. The following chapters are more detailed and examine the evolution, taphonomy and physiology of dinosaurs and then has separate chapters on the dinosaurs clades of Theropoda, Sauropodomorpha, Ornithopoda, Thyreophora, and Marginocephalia. There is a wealth of detail contained in these chapters but laid out in such a way that it is easily readable.

The final part of the book discusses dinosaur ichnology i.e. fossils, tracks, toothmarks, coprolites etc and then birds as modern dinosaurs and possible causes of the extinctions.

Overall this is an amazing book which I enjoyed reading from an amateur point of view. I would recommend it to anyone interested in palaeontology as many of the concepts of burial, retrieval and scientific dating of specimens can be applied to other ancient life forms. It is certainly a book of dinosaurs for geologists.

Eileen Fraser BSc(Hons)(Open) DipEarthSci(Open) FGS